TARGETING AT THE SPEED OF LIGHT

Richard L. Hughey, Lt Col, USAFR
Editor: Colonel James McGovern
23 February 2007

Blue Horizons Paper
Center for Strategy and Technology
Air War College

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **23 FEB 2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Targeting at the Speed of Light**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air University,Air War College,Center for Strategy and Technology,Maxwell AFB,AL,36112**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**83**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

DISCLAIMER

Contents

Page

Illustrations

Page

Tables

Abstract

Is laser energy just a better bullet, bomb or missile? Or will laser energy be a disruptive technology that could enable a U.S. advantage in the operational environment of 2025? If so, how will laser weapon systems be used in the operational environment of the future?

Uncertainty and change are the predictions for the future. Many predict a future of accelerating change. That assumption significantly weakens forecasting estimates and increases risk for any organization. The consequence of a rapidly changing environment, with respect to military capabilities, exposes the United States to increased security risk. The U.S. military, as an instrument of power, must be able to mitigate or overcome security challenges. Laser weapons offer a disruptive capability to minimize these challenges and continue the traditional warfare advantage of the U.S. in the air, space and maritime domains.

Understanding the science and technology of laser energy is crucial to understanding potential strengths and weaknesses as lasers are weaponized. This comprehension allows insight to the value of lasers as a future weapon system. Laser weapon systems will offer speed, ultra-precision, minimal collateral effects and deep magazines that enable temporal and spatial control of the air, space and maritime domains. Laser weapon systems will allow an increase in targets available in the operational environment, increase dynamic targeting and further compress the kill chain. This paper attempts to capture the military utility of laser weapons systems in the context of targeting, weaponeering and operational implications using laser weapon system capabilities described in the *Draft* 2006 Air Force Directed Energy Master Plan employed with current doctrine against present-day targets.

Chapter 1
Introduction

> *A fundamental rule in technology says that whatever can be done, will be done.*
>
> **--Andrew Grove**
> **Intel Corp.**

Accelerating technological development fuels fear that the world is undergoing exponential change. A future of accelerating change enables actors, state and non-state, to threaten U.S. security with new and innovative uses of these technologies. Many propose that this assumption is what should guide the U.S. military should use to guide its decision-making regarding the purchase of new weapons, re-organization, and alter its strategy. If this rapidly changing future is a valid assumption, then disruptive technologies--like laser energy--is a by-product of this change. The U.S. military has stated in its strategy documents that laser weapons are a disruptive technology and important to "protect the U.S., prevent conflict and surprise attack and prevail against adversaries who threaten our homeland, deployed forces, allies and friends."[1]

Laser technology is important because it offers unique characteristics such as speed, ultra-precision, minimal collateral effects and deep magazines that could create advantages in the Operational Environment (OE) of 2025. Due to these characteristics, temporal and spatial changes of the OE may evolve. As a result, the U.S. will need to adapt to the future OE, so as to retain present-day advantages in the air, space and maritime domains. Thus, it will be critical to know and understand laser energy strengths and weaknesses, future laser weapon system capabilities and how they will be operationally employed to create effects in the OE of 2025.

This paper will attempt to show the value-added capabilities that laser weapon systems can offer to the U.S. military in future operations. To demonstrate this, the methodology used incorporates the capabilities outlined in the Draft 2006 Air Force Directed Energy Master Plan (AFDEMP) developed by the Future Concepts and Transformation Division—HQ USAF/A8XC. Specifically included are the laser systems depicted in Air Force Directed Energy Roadmap (AFDER), a subsection of the Draft 2006 AFDEMP, that align technology projects and programs with new mission areas. Since these new mission areas are not well known, this paper will correlate present-day doctrinal concepts and missions with these future laser weapon systems. Also, to better synthesize the practicality of laser weapon system capabilities, this paper will also address their use against present-day targets. In short, today's doctrine employed with future laser weapons against today's targets.

This paper is structured in the following manner. Chapter 2 establishes the case for a rapidly changing operational environment and lasers as a disruptive technology. Chapter 3 establishes the science and technology that governs laser weaponry so that the reader will understand the strengths and weaknesses of laser weapon systems. Chapter 4 describes the capabilities laid out in the AFDER and introduces some complementary capabilities being pursued by other DOD organizations. Chapter 5 depicts the use of laser weapon systems using the present-day doctrine of targeting as well as the tactics, techniques and procedures of weaponeering. Chapter 6 concludes the paper with conclusions, recommendations and implications of laser weapon systems employed in the U.S. military.

Notes

1. Department of Defense, *National Military Strategy of the United States of America*, 2004, iv.

Chapter 2

The Operational Environment of 2025 – Where Are We Going?

> *Change is the law of life. And those who look only to the past or present are certain to miss the future.*
>
> **--John F. Kennedy**

This chapter presents arguments of rapid technological change and how it will affect organizations preparing for future challenges in the OE. A driver of this rapid technological change is "Moore's Law," which predicts an exponential change in a specific technology area. It is being adopted by other technologies experiencing significant change. The expectation of rapid or accelerating technological change produces disruptive challenges for the U.S. Military and makes the OE of the future less predictable. Directed energy, specifically lasers, as a disruptive challenge, will have significant implications in future military operations. These implications will influence the U.S. military in meeting its security challenges in the OE of 2025.

A Mathematical Observation in 1965

Many people in numerous organizations and in countless and varied ways, have attempted to describe what the future holds. Governments have committed vast resources in order to better depict the appropriate path to take regarding their respective futures. As new technology develops and innovative technological breakthroughs occur, each organization's best guess of the future is revisited, revised and re-plotted. The common element in many of these futures is Moore's Law. What is it and why is it important?

Moore's Law is the empirical observation that the transistor density of integrated circuits, with respect to minimum component cost, doubles every 12 months.[1] Intel co-founder, Gordon

Moore, made his famous comment in 1965 when there were approximately 60 transistors on a chip. In 1975, Moore adjusted his prediction from 12 months to 24. From 1965 to 2004, Moore's Law effectively described transistor density of integrated circuits with respect to component cost; in the latter year Intel placed 592 million transistors on its Itanium 2 chip.[2]

Gordon Moore believes his mathematical prediction will hold for another 10-20 years. He states, "…it can't continue forever. The nature of exponentials is that you push them out and eventually disaster happens."[3] The fact is, this mathematical prediction doesn't *govern* the progress of semiconductors; it simply attempts to *describe* it. Until a deviation in the transistor density of integrated circuits with respect to component cost occurs, people will continue to view it as *law* instead of merely a *theory*. In the mean time, this research paper will continue under the assumption that Moore's Law holds for another 20 years as a valid mathematical observation.

Disruption – Fact or Fiction?

As Moore's Law attempts to describe the future progress of semiconductors, the U.S. military attempts to describe the progress of future technologies that could pose as a disruptive challenge to the security of the U.S. Along with traditional, irregular and catastrophic challenges, the 2005 National Defense Strategy states, "disruptive challenges may come from adversaries who develop and use breakthrough technologies to negate current U.S. advantages in key operational domains." Breakthrough technologies include "revolutionary technologies and associated military innovation (that) can alter long established concepts of warfare." The

Irregular Challenges
Catastrophic Challenges
Defeat Terrorist Networks
Prevent Acquisition Or Use Of WMD
Defend Homeland In Depth
Shape Choices Of Countires At Strategic Crossroads
Today's Capability Portfolio
Traditional Challenges
Disruptive Challenges

Figure 2-1: Future U.S. Security Challenges[4]

technological advances include "biotechnology, cyber operations, space or directed energy weapons" which could be used to exploit vulnerabilities and offset current advantages of the U.S. and its partners.[5]

Harvard Business School professor Clayton Christensen states: "it is the combination of new **disruptive technologies** which could have significant impact on nations such as the United States."[6] The 2006 *Quadrennial Defense Review* (QDR) illuminates the Peoples Republic of China as an emerging military peer that is moving to "field disruptive military technologies that could over time offset traditional U.S. military advantages absent U.S. counter strategies."[7] Alternatively, **disruptive innovation** could, in fact, be an enabler for the U.S. to leverage innovative people as stated in Joint Vision 2020; "the pace of technological change, especially as it fuels changes in the strategic environment, will place a premium on our ability to foster innovation in our people and organizations across the entire range of joint operations."[8] In the end, people combining technologies and capabilities, in innovative ways, enable or disable the U.S. military's advantage, both symmetric and asymmetric.

Are these U.S. strategy documents introducing valid arguments regarding disruptive technology? According to Harvard Professor, Clayton Christensen, there are two technologies: sustaining technologies and disruptive technologies. Sustaining technologies are simply technologies that improve product performance. These are technologies that most large organizations are familiar with; technologies that involve improving a product that has an established role in the market. For example, block upgrades to an existing weapon system. Most large companies are adept at turning sustaining technology challenges into achievements. Christensen claims that large companies have problems dealing with disruptive technologies.

Disruptive technologies are generally "cheaper, simpler, smaller, and, frequently, more convenient to use." Disruptive technologies, according to Christensen, occur less frequently, but when they do, they can cause the failure of highly successful organizations that are only prepared for sustaining technologies.

In contrast, independent author, John C. Dvorak, states in his 2004 PC Magazine article, “The Myth of Disruptive Technology” that…

> …there is no such thing as a disruptive technology. There are inventions and new ideas, many of which fail while others succeed. That's it…One problem in our society is the increasing popularity of false-premise concepts that are blindly used for decision-making. The amount of money squandered during the dot-com era because of ‘paradigm shifts’ and ‘new economies’ is staggering. People actually believed that all retailing would be online and that all groceries would be delivered to the home as they were in the 1920s, despite changes that make delivery impractical. Who cares about reality? We have a disruptive technology at work![10]

Despite the author’s skepticism of disruptive technology, U.S. military decision makers still need to assess and systematically prepare for the future OE. After analyzing the following forecasting documents; *Air Force 2025*, *Alternate Futures for 2025: A Mid-course Update*, NIC 2020 Project – *Mapping the Global Future*, and The Committee on Defense Intelligence Agency Technology Forecasts and Reviews - *Avoiding Surprise in an era of Global Technology Advances*, the common theme is an OE where threats come from dispersed groups or even super-empowered individuals. In response, the U.S. must counter with increased intelligence resources, multinational cooperation, strict homeland defense measures, and global engagement. While the Bush Administration has wisely started down this path, sustaining such policies without breaking the budget, treading upon civil liberties, or over-committing troops presents challenges. If technology growth becomes exponential, these problems multiply, with the danger of falling behind technologically becoming as serious as countering the myriad of threats.

Planning for and adapting to these threats is the *sine qua non* for 21st century national decision makers.[11]

It is the opinion of the author that a technology is <u>disruptive only when rival organizations that, for reasons of their own, fail to compete for the new capability that the "disruptive technology" is attempting to fill</u>. In other words, if the U.S. fails to understand, invest and exploit a new technology that may compliment or replace current capability, it runs the risk of failing in a certain realm where a competitor has chosen to compete. Because there are many variables at play in today's OE, attempting to correlate or identify what exactly defines a disruptive technology is problematic – especially in an era of rapid change. Contrasting this problem, the <u>ultimate</u> advantage of the U.S. military, according to the 2006 QDR, is "superbly trained, equipped, and highly dedicated people."[12] Therefore, continuing to invest in the development of the people serving in DOD should be an ongoing focus for the future while attempting to compete in disruptive technologies.

In this dynamic OE, the ability to adapt to changing circumstances is critical for accomplishing missions, overcoming operational obstacles, and winning. In other words, the focus of the changing environment should not be *all* about new or disruptive technology. It's also about finding, positioning, training, equipping and unleashing resourceful people to compete for U.S. interests. In short, it is the people who are developing new technology and performing technical feats, not the technology.

There are also creative feats that people perform to use a new technology – in a way engineers had not envisioned. More succinctly expressed by John Boyd, in his trinity of emphasis, "people first, ideas second, things third." As the U.S. moves from an industrial age to an information age military, the word relationships in Figure 1-5, correlate the transition in our

thinking. Accordingly, technological inventions, prediction models, or independent instruments

From	To
Invention	Innovation
Linear innovation model	Dynamic innovation mode
Build to forecasted demand	Sense and respond to demand
Independent	Interdependent
Single discipline	Multiple discipline
Product functions	Value to customer
Local R&D teams	Globalized 24x7 R&D teams

SOURCE: COC (2004). Reprinted with permission from the Council on Competitiveness.

Table 2-2: Invention to Innovation[13]

of power will not mitigate the risks of the dynamic nature within the global security environment. Innovative people, interdependent services and integrated instruments of power will be better equipped to respond to the dynamic security environment needs of U.S..

The Disruptive Writing on the Wall

U.S. military decision-makers have accepted a future of accelerating change as a critical variable for considering forthcoming technologies. U.S. examples are seen in the writing expressed in the 2006 QDR and by the formation of the Disruptive Technology Office (DTO), which administratively exists under the National Security Agency (NSA). With a larger share of national security initiatives currently focused on defeating fundamentalist ideologies using terrorism – a critical future amalgamation is the combination of disruptive technologies with people willing to employ them using terrorist methods. National security decision-makers believe that with an accelerating change rate, technological tools will become more readily available to more of the world's population, and, therefore, presume the likelihood of a disruptive or catastrophic event is more credible.

An important consideration regarding disruptive technologies is the appropriation of tax dollars toward research and development to enable these future technologies to move toward

selection, acquisition and purchase of new military capabilities. While the U.S. continues to dominate other nations of the world in terms of total R&D spending (see Figure 1-5),

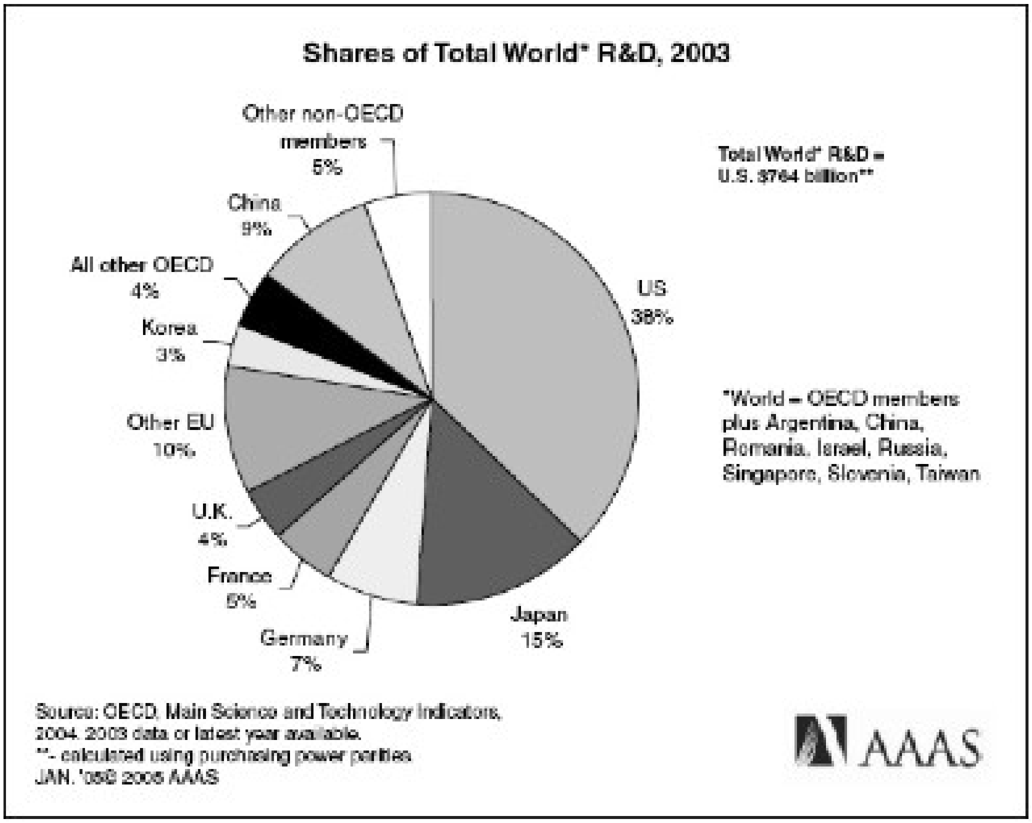

Figure 2-3: World R&D expenditures[14]

comparisons of R&D spending as a ratio of gross domestic product (GDP) provide a different picture. The National Academy of Sciences reports that the United States lags Japan in total R&D as a percentage of GDP (2.67 percent versus 3.12 percent in 2002) as well as in business R&D (1.87 percent versus 2.32 percent in 2002). "Between 1995 and 2002, China doubled its spending on R&D when calculated as a percentage of GDP (1.2 percent in 2002). During that same period, Israel increased its spending from 2.74 percent to 4.72 percent of GDP, a ratio higher than that of any other Organization for Economic Co-operation and Development (OECD) nation."[15] These trends are indicative not only of the growing importance that nations are placing on R&D but also of prospective challenges to U.S. technological leadership. The

long-term commitment of other countries to basic high-technology funding is particularly significant and needs the attention of national security decision-makers.

Conclusion

In the OE of 2025, acquisition timelines will be significantly compressed to be effective. Because of the accelerating rates of technological change, military capabilities determined in 2006, but not fielded until 2020 or later, risk failing to achieve the capability advantage anticipated and are less likely to be effective at the time of initial operating capability (IOC).[16] This technology development-acquisition cycle has recently shown to create a lower net purchase in numbers of weapon systems inducing yet another decline in the return on anticipated capability. Therefore, in the author's opinion, when considering new capabilities, it will be necessary to accelerate the technology development-acquisition cycle, as compared to past acquisitions, in order to utilize the technology before it is obsolete or countered militarily.

As long-range forecasts become less reliable, short prediction models will require more accuracy. If the accuracy is not attainable, then higher risk will be assumed. Decision-making will become more critical as the risk increases and those people in leadership positions will be expected to reduce risk by new means. In the author's opinion, a solution is to empower innovative people to mitigate local risks by execution that is decentralized. This will enable more adaptive and responsive actions that can protect, prevent, and prevail against adversaries in the short term.

Notes

1. Gordon Moore, "Cramming more components onto integrated circuits," *Electronics* 38, no. 8 (April 19, 1965), Intel Corporation website, ftp://download.intel.com/museum/Moores_Law/ Articles- Press_Releases/Gordon_Moore_1965_Article.pdf, (accessed 11 Feb 07).

2. Intel Corporation, “Moore’s Law Timeline,” ftp://download.intel.com/pressroom/kits/events/ moores_law_40th/MLTimeline.pdf, (accessed 11 Feb 07).
3. Manek Dubash, “Gordon Moore speaks out,” interview with Gordon Moore, *Techworld*, 15 April 2005, http://www.techworld.com/news/index.cfm?newsid=3477 (accessed 26 Nov 2006).
4. Department of Defense, *National Defense Strategy of the United States of America*, March 2005, 2-4.
5. Ibid.
6. Christensen, Clayton M., *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*, Boston, MA: Harvard Business School Press, 1997, 19.
7. Department of Defense, *Quadrennial Defense Review Report*, February 6, 2006, 29.
8. Department of Defense, *Joint Vision 2020*, June 2000, 3.
9. Christensen, Clayton M. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*, 27.
10. John C. Dvorak, “The Myth of Disruptive Technology,” *PCMAG.COM*, 17 Aug 2004, http://www.pcmag.com/article2/0,1759,1628049,00.asp (accessed 26 Nov 2006)
11. Col Ken Rizer, “Alternate Futures for 2025: A Mid-course Update” (Air War College, Blue Horizon’s Future Study), 47.
12. Department of Defense, *Quadrennial Defense Review Report*, February 6, 2006, A-6.
13. National Academy of Sciences Committee on Defense Intelligence Agency Technology Forecasts and Reviews, *Avoiding Surprise in an Era of Global technology Advances*, ISBN 0-309-54916-7, (Washington D.C.: National Academy Press, 2005), 13.
14. Ibid, 12.
15. Ibid, 11.
16. An example is the F-22A, which started developmental test and evaluation in 1986, reaching initial operational status in 2004. From “Factsheets: F-22A Raptor,” *Air Force Link*, United States Air Force, June 2006, http://www.af.mil/factsheets/factsheet.asp?id=199 (accessed 4 Dec 2006).

Chapter 3

Laser Science and Technology – what is it?

> *We live in a society exquisitely dependent on science and technology, in which hardly anyone knows anything about science and technology.*
>
> **--Carl Sagan**

The technology of laser energy is highly complex requiring specific education and training to fully understand the science associated with lasers. This chapter introduces the scientific and technological background of the electromagnetic (EM) spectrum to establish a basic foundation of understanding regarding laser technology. It attempts to offer an explanation of the physics regarding laser energy as a waveform, and why it is different than other types of light. The chapter also describes how laser energy interacts with material, the characteristics and complexity of a laser system, and the limitations of those systems when applied outside the laboratory. It closes with a description of laser weapon system lethality as it is weaponized for military use.

EM Spectrum – The Source of Disruptive Technology

The energy sources for directed energy (DE) technology are the radiation waveforms described by the EM spectrum. The EM spectrum (see Figure 3-1) can be expressed in terms of energy, wavelength, or frequency. Frequency is measured in cycles per second (which is called a Hertz), wavelength is measured in meters, and energy is measured in electron volts. The reason for the different mathematical expressions stem from the view that scientists use whatever units are easiest for their environment – here mostly determined by what part of the EM spectrum they are working with.[1]

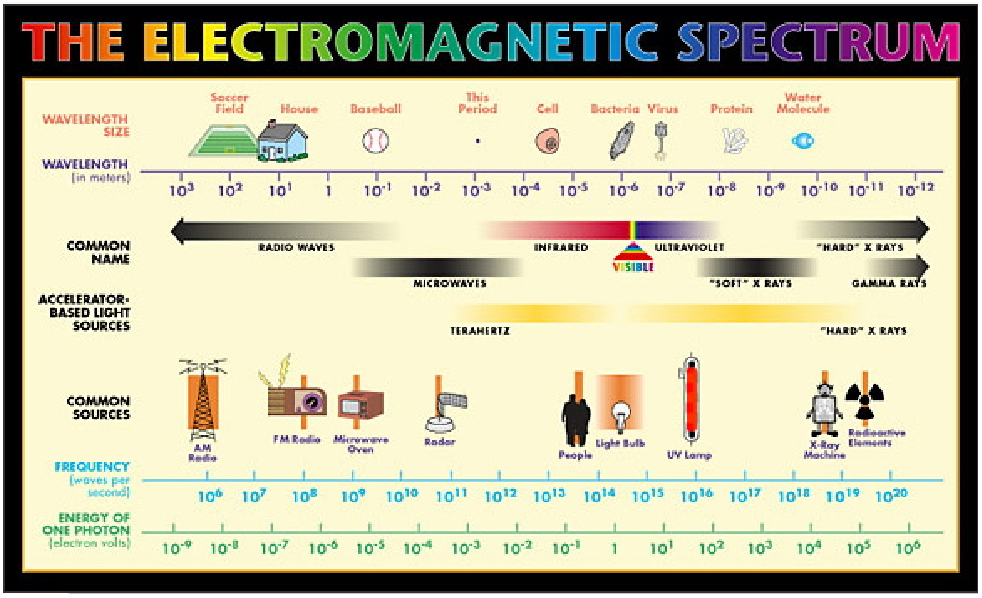

Figure 3-1: The electromagnetic spectrum[2]

EM radiation can also be described as energy, in terms of a stream of photons, which are massless particles each traveling in a wave-like pattern and moving at the speed of light. Each photon contains a certain amount (or bundle) of energy, and all EM radiation consists of these photons. The amount of energy a photon has makes it sometimes behave more like a wave and sometimes more like a particle. This is called the "wave-particle duality" of light. It is important to understand that this is not about **what light is**, but about **how it behaves**. Low energy photons (such as radio) behave more like waves, while higher energy photons (such as X-rays) behave more like particles.[3] A **photon's energy is inversely proportional to its wavelength**. This means that each photon of shorter wavelength (such as violet light) carries more energy than a photon of longer wavelength (such as red light).

LASER Light – Why Is It Different?

A LASER (Light Amplification by Stimulated Emission of Radiation) generates energy (photons) by exploiting a quantum mechanical effect called "stimulated emission." Laser light

has the following properties: it is **monochromatic** - it contains one specific wavelength of light, it is **coherent** - each photon moves in step with the others, it is **directional** - it has a very strong, concentrated, tight beam. These properties allow lasers to focus a specific wavelength of photons on a very small spot and therefore, deposit an enormous amount of energy on that spot. Non-laser light sources typically generate incoherent, unfocused beams of light at a variety of wavelengths, prohibiting certain applications.

Because of the three qualities of laser light (monochromatic, coherent and directional), the output beam of the laser may be highly collimated (light whose rays are parallel and thus have a plane wavefront), that is, having a very small beam divergence. However, a perfectly collimated beam cannot be created, due to diffraction (bending, spreading and interference of waves emerging from an aperture). But a laser beam will spread much less than a beam of incoherent light. The beam remains collimated over a distance, which varies with the square of the beam diameter, and eventually diverges at an angle that varies inversely with the beam diameter. Such a divergent beam can be transformed into a collimated beam by means of a lens or system of lenses. These lenses are referred to as *optics* in the lexicon of laser terminology.

The application of laser energy for military utility comes in many forms of lethal and non-lethal thermal effects. Lethal and non-lethal thermal deposit of photonic energy is the focus of the following basic review/discussion. The term **Power** refers to the rate at which work is done, or the amount of energy applied per unit time: **Power** = Energy/Time = Joules/sec (expressed in Watts). The term **Power Density** or **Irradiance** (sometimes referred to as brightness), refers to the amount of power per unit area: **Irradiance** = Power/area (expressed in Watts/cm^2). The term **Fluence** refers to the amount of energy applied per unit area: **Fluence** =

(power*time)/area = ((Joules/s)*s)/cm^2 = Joules/cm^2. These factors are tied to the components that enable the laser certain unique capabilities.[4]

Irradiance is the power output of the laser and **fluence** is the energy applied on the surface of the target. Fluence is the kill mechanism for a laser weapon system. The coupling of intense laser energy with target material can result in melting, vaporization, ejection of atoms and the creation of shock waves. Fluence is affected by the wavelength of the medium, beam quality, power out of the laser, range to the target, tracking of the target, angle of incidence (the 2 dimensional approach to the surface of the target), and the reflection, refraction, and absorption of the material on the target. All these factors (discussed shortly) contribute to a laser's lethality on a target and require understanding of the physical response of a target to laser energy.

Laser-Material Response

Examining what happens when the laser energy interacts with target material, it is convenient to think of this interaction in three parts. These three parts influence each other and take place simultaneously. First, laser light couples with the material - recall the wave-particle duality of light. The net result of the coupling is the conversion of some fraction of the laser energy into thermal and/or mechanical energy. Second, a thermo-mechanical signal is propagated into the material. The details of this propagation play a prominent role in determining the net effect of the irradiation. Third, the induced effect that the thermo-mechanical signal has on the material results in melting or vaporization, shock loading, crack propagation, and other effects. Alternatively, when metal begins to melt, its optical reflectivity and thermal diffusivity change markedly, and this changes the coupling and the energy flow.[5] Understanding a material's response to laser energy is critical in predicting effects of laser

weapon systems (LWSs) against particular materials that are expected to be present in the OE of the future. This will allow the U.S. Military to advantageously shape the OE.

Laser Weapon System Characteristics

The physical processes of laser-material interaction are required to understand the laser energy weapon system capabilities and limitations. When laser energy strikes the target material, some of the energy is reflected and some of it is absorbed and the responses are due to the microstructures (atomic level) of materials.

As previously described, laser energy has a relational feature because materials show different absorption capacities with different laser wavelengths. This knowledge is vital for proper target weaponeering with a particular LWS of a particular wavelength. With different absorption of lasers with different wavelengths, dependence of absorption on wavelength is decided by the microstructure and electromagnetic properties of the material. For example, copper has an absorptivity of 2% for 10.6 micron CO2 lasers, but has much higher absorptivity for UV lasers (about 60%).[6] The target material make-up will be vital information for proper assessment of the laser-material response and achieving desired lethality. Also, shorter wavelengths carry more power than longer wavelengths. In contrast, shorter, more powerful wavelengths have less atmospheric propagation characteristics as compared to longer wavelengths. Bottom line, the long wavelengths have less power, but propagate through the atmosphere better than short wavelengths.

Beam control refers to internal laser sub-systems that affect beam quality of the LWS. It includes adaptive optics, low power lasers, aero-optics and anti-jitter system technologies. Depending on the laser, beam control can include initial processing of the beam to shape it and eliminate unwanted off-axis energy, or can include wavefront shaping and/or phase control. For

a set of given environmental conditions, these sub-systems collectively enable the laser weapon system, as a whole, to operate at the highest lethality.

Adaptive optics within the laser weapon system performs beam shaping and phase control by deforming the mirrors within the laser optical system. Adaptive optics use atmospheric measurements, calculated as fast as every 100th of a second by a low power laser, in order to pre-deform the beam so that when power is applied, laser energy arrives coherent at target range. These atmospheric measurements account for humidity, dust, water vapor and atmospheric turbulence and are critical to achieving the fluence required for the desired lethality.

When the laser is employed from a high-speed aircraft, a major challenge for beam control is accounting and adjusting for atmospheric turbulence (optical turbulence). The turbulence is generated from the flow if air around the aircraft. Aero-optics is used to adapt to

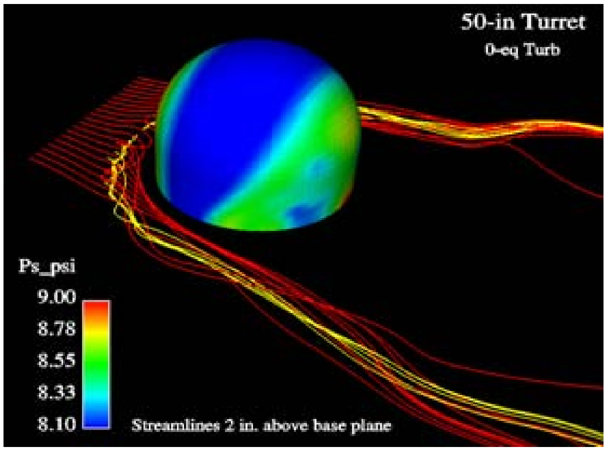

Figure 3-2: 50 inch Laser Turret with air flow disturbance[7]

the aerodynamic wavefront that is present when the laser-pointing device moves into the air stream (see Figure 3-2). This beam control application is both computer intensive and optic intensive because it accounts for airspeed, altitude, air temp, vertical velocity and off-axis

pointing of the beam in relation to airflow. The faster the aircraft is traveling, the more dramatic the impact of the aero-optics sub-system's input to the laser weapon system performance.

Beam control is also affected by vibration from the host platform (i.e. aircraft or ship). Precise stability is needed so the beam does not "blur" due to vibration, as it is departs the laser. Anti-jitter systems provide the stability needed to reduce the vibration and allow the beam to arrive as a coherent wavefront at the target surface. Anti-jitter system advancements are expected to meet requirements of laser weapon system described in the Draft 2006 AFDEMP as development moves forward.

Beam quality refers to effects on the beam after it leaves the aperture of the laser weapon. It is affected by size of the aperture, opening in the aperture and diffraction. Aperture size is limited by the platform size and weight limitations. Spot size is determined by the size and shape of the beam at contact with the target. For instance, a laser beam's 2-foot diameter spot on target at 20 miles might carry 100kJ/cm^2. If one were to use a lens to focus that spot size down to 1-foot diameter at the same target range, it would carry 200kJ/cm^2—twice as much fluence on ½ the spot size on the target. That means the desired target effects will be achieved sooner.

Generating the power to drive a military laser and its sub-systems requires substantial mega watts (MW) of power. Chemical reaction and electrical power sources are the current means for generating this power requirement. The challenge of power efficiency for electric or solid-state lasers (SSLs) is not as great as it is for chemical lasers. The chemical laser trade off is great power throughput efficiency but a limited magazine due to finite amount of chemicals available on a platform. For an SSL, the trade off is poor power throughput efficiency but with a shot magazine only limited by duty cycle for thermal dissipation. The SSL requires a large power generation that currently limits the size of the host platform to transport size aircraft and

semi tractor-trailers. The SSL efficiency tradeoffs are present day limitations and expected to improve through technological progress to enable installation on a fighter or vehicle by 2025. Achieving sufficient power and output efficiency is critical to attaining sufficient damage thresholds for target materials.

A primary requirement for a future LWS is placing the laser spot on desired aimpoint and maintaining that aimpoint on the target until desired lethality is achieved. A 2025 LWS fire control system (FCS) should be designed to utilize internal or external acquisition sensors for initial pointing and tracking. Ideally, a low power pulse of the LWS to find, fix, and track the target while the FCS is identifying the target with automatic target recognition (ATR) technology while automatic aimpoint recognition (AAR) technology is determining the desired aimpoint. This particular technology is being researched and developed by the Defense Advanced Research Program Agency (DARPA).

Like any EM spectrum waveform, the farther away from the waveform source, the weaker the power per unit area. The impact of range to target for LWS is significant because it is affected by the spot size and power out. These variables are important since the fluence at target range is inversely proportional to square of the range. In other words, if range to target is increased by a factor of 2, then fluence decreases by a factor of 4. This mathematically identifies the relationship of power out to beam quality when all other variables are held constant. Therefore, spot size and system power out are central to solving for the fluence at target range.

Attack Geometry

The angle of incidence θ_1 of a ray or beam is the angle measured from the ray to the surface normal.[8] (see Figure 3-3)

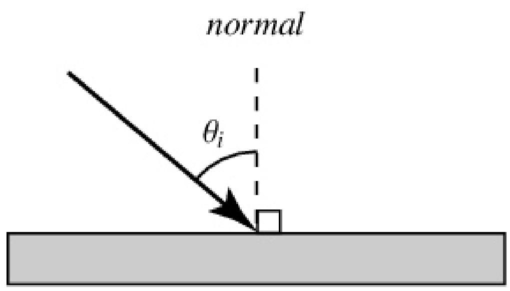

Figure 3-3: Angle of Incidence

The angle of reflection θ_r of a ray or beam is the angle measured from the reflected ray to the surface normal.[9] (see Figure 3-4)

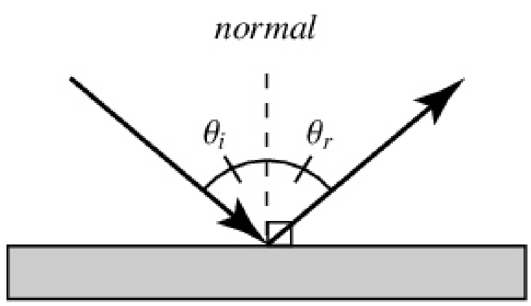

Figure 3-4: Angle of Reflection

From the law of reflection, $\theta_i = \theta_r$, where θ_i is the angle of incidence. θ_r is measured between the ray and a line normal to the surface that intersects the surface at the same point as the ray.

When rays or beams strike a surface and are refracted through the surface they obey Snell's law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

where n_1 is the index of refraction of the material the incident ray is traveling through, n_2 is the index of refraction of the material the refracted ray travels through, θ_1 is the angle of incidence, and θ_2 is measured between the ray and a line normal to the surface that intersects the surface at the same point as the ray.[10]

Analyzing Snell's law one can find certain circumstances under which the ray will not be refracted, instead it is reflected. This is the case when $n_1/n_2 > 1$. When this is the case, a critical angle θ_{crit} is found from the relation

$$\sin\theta_{crit} = n_2/n_1$$

When $\theta_1 > \theta_{crit}$ the ray is reflected. When $\theta_1 = \theta_{crit}$ the ray travels along the surface and tangential to it.[11] (see Figure 3-5)

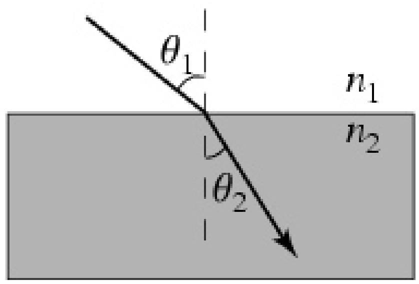

Figure 3-5: Angle of Refraction

Refraction is important when considering employment a laser through a transparent medium – like a glass window. Some of the laser energy will be absorbed by the glass, some of it will go through the glass at an angle different than that of the angle of incidence and some of the energy will be reflected and scattered away from the glass. There could be considerable risk when employing an eye-damaging wave-length laser in this situation. This risk needs to be assessed before eye-damaging wavelenth lasers are used where civilians/non-combatants within the hazard area could receive a dose of reflected laser energy to their eyes. AFRL/DE believes that hazard extends to 75 meters from the desired point of impact (DPI).[12]

Dwell Time

Given the laser pulse duration, one can estimate the depth of heat penetration, which is the distance that heat can be transferred during the laser pulse. $D=\sqrt{(4*\alpha*dT)}$ where D is the

depth of heat penetration, α is the diffusivity of materials (for that laser medium type) and dT is the pulse duration. Conversely, one can estimate the minimum pulse duration needed to penetrate a certain depth. Then we have: $dT=D^2/(4*\alpha)$.[13] This estimate will determine the duration, or **dwell time**, required to achieve the desired effect (thermal penetration) for the target. Therefore, it will be particularly important to understand what part or component of a target is the aimpoint. After determining the target aimpoint, then determine the expected absorption in order to define the fluence to achieve sufficient lethality. Lastly, target orientation in reference to the LWS should be considered to maximize the angle of incidence so as to increase absorption and minimize reflection/refraction to, thereby, minimize collateral effects.

Lethality defines the total energy and/or fluence level required to create desired effects for specific target materials. The laser energy must couple efficiently with the target, and it must

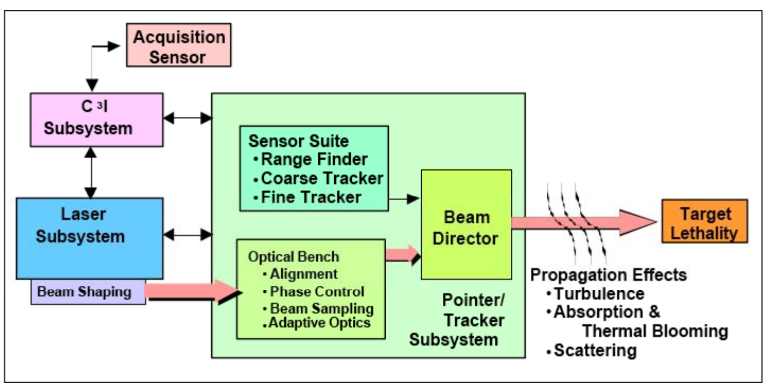

Figure 3-6: Common High Energy Laser Technology[14]

exceed a failure threshold that is both rate-dependent and material-specific. Laser output power, beam quality, spot size and range to target are key variables for determining whether a LWS is capable to deliver sufficient fluence to achieve the desired lethality for a specific target (see Figure 3-6).

Conclusion

In summary, the numbers of sub-systems required for a laser weapon system to be operationally effective is significant. These sub-systems require a high degree of reliability, with minimal variation in performance, in order to meet the total system requirement for the laser to be employed. Therefore, systems integration and reliability are the most significant challenges in the development of future laser weapon systems.

Notes

1. NASA Goodard Space Flight Center, "Measuring the electromagnetic spectrum," http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html/ (accessed 15 Dec 06).
2. Lightsources.org, "What is a Light Source?" http://lightsources.org/cms/?pid=1000166, (accessed 30 Nov 2006).
3. NASA Goodard Space Flight Center, "Measuring the electromagnetic spectrum," http://imagine.gsfc.nasa.gov/docs/science/know_l2/emspectrum.html (accessed 15 Dec 06).
4. Dr. Larry Grimes, AFRL/DE, "HEL Tutorial," presentation, 22 Apr 03, slide 34.
5. Shore Laser, "More About Lasers," http://www.shorelaser.com/AboutLasersDet.html (accessed 30 Nov 06).
6. Columbia University, "Laser Machining Process," http://www.mrl.columbia.edu/ntm/level1 /ch03/ html/l1c03s03.html (accessed 02 Dec 06).
7. David Leggett, *Deliver On-Demand Lethal Effects to Difficult Targets with Ultra Precision*, (AFRL/VA), power point presentation slide 12.
8. Wolfram Research, "Angle of Incidence," http://scienceworld.wolfram.com/physics/Angleof Incidence.html (accessed 02 Dec 06).
9. Wolfram Research, "Angle of Reflection," http://scienceworld.wolfram.com/physics/Angleof Reflection.html (accessed 02 Dec 06).
10. Wolfram Research, "Angle of Refraction," http://scienceworld.wolfram.com/physics/Angle ofRefraction.html (accessed 02 Dec 06).
11. Wolfram Research, "Critical Angle," http://scienceworld.wolfram.com/physics/Critical Angle.html (accessed 02 Dec 06).
12. HQ USAF/XPXC, *2005 Air Force Directed Energy Master Plan Vol I* "Draft", 28-29, (FOUO), information extract is unclassified.
13. Columbia University, "Laser Machining Process," http://www.mrl.columbia.edu/ntm/level1 /ch03/html/l1c03s03.html (accessed 02 Dec 06).
14. Defense Science Board Task Force, High Energy Laser Weapon Systems Applications, June 2001, 3-4.

Chapter 4

Laser Capabilities – Now to 2025

> *No new weapons can be introduced without changing conditions, and every change in condition will demand a modification in the application of the principles of war.*
>
> **--Major-General J.F.C. Fuller**
> **Armoured Warfare, 1943**

Laser weaponization is intuitive in today's technologically progressive society. This chapter simply depicts technology programs associated with and depicted in the 2006 AFDEMP as well as other similar programs. It discusses air/surface/space based laser weapon systems, sub-systems and associated laser energy systems and the intent of their use in the future. This chapter attempts to connect the science and technology from Chapter 3 with the capabilities being developed today to be employed in future military operations.

Directed Energy Technology

DE technology (laser, high power microwave, millimeter wave and particle beam technology) is no exception to the category of future technologies that could be both costly and potentially disruptive. As evidenced by the language in the 2006 QDR, AF Road Map and Strategic Plan as well as AF Concept of Operations (CONOPS), U.S. civilian and military leaders are already incorporating DE technology into their forecasts to better discern what we as a nation need to prepare for. As technology influences change, the rate of change could influence relative power, not political, but military power in which the U.S. has current advantage. Our national security, defense department and military decision-makers recognize that DE technology is an opportunity to maintain that advantage.

Progression of various DE technologies from the laboratory through Advanced Concept Technology Demonstrations (ACTD) to Initial Operating Capability (IOC) will be one of the first opportunities to validate this accelerated process. This validation is critical to show decision-makers the value of DE weapons. The advantage gained by being first to field a DE weapon is comparable to being first to market with a new product. Because of the operational characteristics of DE technology, it will be important to field capabilities ahead of competitors, state and non-state, in order to prevent possible disadvantage by losing control of the commons--the air, space and maritime domains.

Laser weapons deliver effects at the speed of light. The speed of light is 186,000 miles per second or, said another way; light travels around the Earth seven times in one second. The control of the commons is a present-day prerequisite for forcible entry into a surface conflict within the borders of another nation. As the U.S. attempts to maintain its advantage over control of the commons, the applicability of lasers is even more magnified as a complementary capability to current military means.

Control of the commons is even more essential when seeking to gain control of urban environments. Maintaining control of the commons allows the U.S. military to use air, space and maritime capabilities applied on land and urban areas while ground forces are free from adversary attack using the commons. U.S. ground forces maintain freedom to maneuver on land and in urban areas when control of the commons is maintained. Because the U.S. is preconditioned to attaining superiority of the air, space and maritime domains, the application of LWS capabilities will further enable the U.S. military to continue this degree of control.

Laser energy systems (LES) come in many forms from low energy lasers for communication to multi- and hyper-spectral imaging. In contrast, laser weapon systems (LWS)

are capable of instant, precise, lethal and non-lethal effects, for offensive and defensive application with minimal collateral damage. Combining information technologies with laser technology could provide an innovative path for disruptive effects against state and non-state threats. These technologies applied toward targeting in the 2025-2030 timeframe, are the mainstay of this paper.

The Present Situation

Department of Defense (DOD) has validated the worth of DE weapons and, more specifically, high-energy laser weapons systems (HELWS) through increased funding of programs as well as establishment of the High Energy Laser Joint Technology Office (HEL JTO). Supporting evidence is found in reports such as the Office of the Secretary of Defense, High Energy Laser Weapon Study and programs currently sponsored by DOD, such as the Joint High Power Solid State Laser (JHPSSL) program. JHPSSL has a CY08 goal of 100kW solid state laser laboratory demonstration. The future value of LWS merits academic studies and program funding with the expectation of a capability that will payoff with a continued asymmetric advantage for the U.S. military.[1]

First generation LWS devices and their sub-systems are currently large, expensive and functional only for application in unique situations such as ballistic missiles and Special Operations Forces (SOF) "covert attack" for the near-future (2008-2015) OE.[2] The far-future (2016-2025) LWS systems will evolve from these present-day designs. The 2006 AFDEMP offers complementary HEL technology programs that are currently funded by DOD. It also depicts future high energy LWS and complementary capabilities as follows:

Air-based LWS

Airborne Laser (ABL) is a Boeing 747 platform with Chemical Oxygen Iodine Laser (COIL). Sponsored by Missile Defense Agency (MDA) as part of the layered Ballistic Missile Defense (BMD), ABL is currently at Technology Readiness Level 5 (component validation in relevant environment). ABL employs its laser in the 1.35-micron (1350nm – near IR) part of the EM spectrum. ABL's 1-megawatt (MW) chemical laser is designed to shoot down ballistic missiles in the boost phase of flight with lethality out to 200km. It incorporates a tracking laser to find the missile and cue a targeting laser to precisely place a high energy laser spot, emanating from the 1.5 meter aperture, on the most vulnerable spot/component on the missile (see Figure 4-1).

Figure 4-1: Airborne Laser

Advanced Tactical Laser (ATL) is currently being fitted on a C-130 platform as an ACTD under the Next Generation Gunship (NGG) program. ATL is sponsored by Air Force Special Operations Command and employs a near-IR, 100kW chemical closed system COIL laser and will, in the future, be fitted with a 100kW SSL laser designed for employment against surface targets while in support of SOF operations (see Figure 4-2-).

Figure 4-2: Advanced Tactical Laser

Laser Strike Fighter (LSF) is a F-35 platform variant, fitted with a SSL where the lift fan exists on the Vertical Short Takeoff and Landing (VSTOL) version.

Figure 4-3: F-35 - Laser Strike Fighter variant

The 1MW shaft that would power the lift fan powers the SSL. Currently in concept form, this LSF will be a 1 to 1.3 micron 100kW SSL[3] to provide a maneuverable, Low Observable (LO) sensor-shooter capability that will offer access to denied areas for employment (see Figure 4-3).

Surface-based LWS

Ground-Based Laser (GBL) is currently a U.S. Air Force/U.S. Army-sponsored program designed as an anti-satellite (ASAT) capability. Stationary GBLs will offer the highest power output as they are less restricted by footprint (size & weight). However, mobile GBLs will still have limited power output due to their size and weight limitations. Used in combination with relay mirrors (see Figure 4-4), the extension of range and redirection beyond line of sight allow GBLs to cover both air and surface targeting across a wide area.

NOTE: The Peoples Republic of China and Israel are currently developing GBLs.[4] In fact, Israel and the U.S. Army partnered to develop the Mobile Tactical High Energy Laser (MTHEL) prototype weapon system, which uses mobile platform-based elements integrated into the Joint

Figure 4-4: Ground Base Laser in a C-RAM role

Common Air and Missile Defense architecture to counter rockets, artillery and mortars (C-RAM), as well as unmanned aerial vehicles, cruise missiles, and tactical air to surface missiles.[5] Additionally, according to DefenseNews.com, the Peoples Republic of China has successfully developed and fired a high energy GBL at a U.S. satellite.[6]

Maritime-Based Laser (MBL) is currently sponsored by the U.S. Navy pushing for the Free Electron Laser (FEL) concept that will be tied in with "electric boat" technology development (see Figure 4-5). The FEL will offer *tunable* frequency allowing the Navy to utilize this system in a variety of environmental conditions, circumstances and settings.[7]

Figure 4-5: Maritime Based Laser – FEL on surface ships

Space-based LWS

Space-based Laser (SBL) is a high risk technology development area that was terminated in 2001 when the MDA re-scoped SBL work into a technology development effort. Costs required to developed and transport this high-risk capability into the space domain did not promise the return on investment. SBL R&D resources were reallocated toward other MDA projects.[8]

Relay Mirrors

Air and space **relay mirror systems** are powerful laser enablers. Utilizing a low/high-altitude airship or a low Earth orbit satellite as a platform, mirror systems overcome line of sight issues by reflecting the laser to the target. These relay mirrors offer range extension, alternative ISR capability, target identification and designation for non-lethal and lethal target engagement.

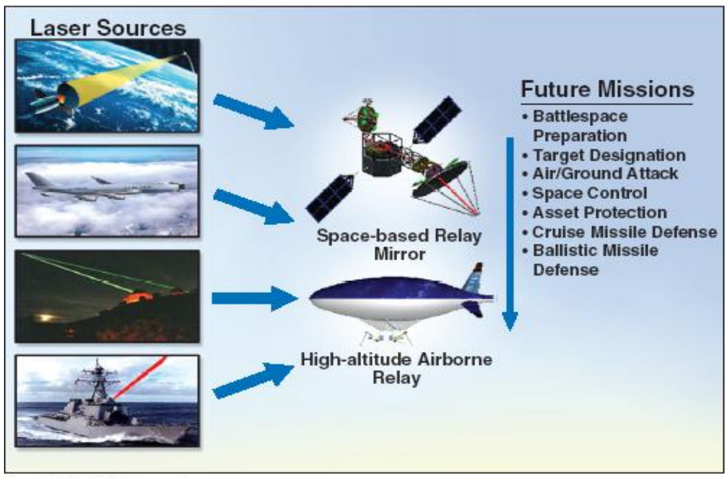

Figure 1. The EAGLE concept

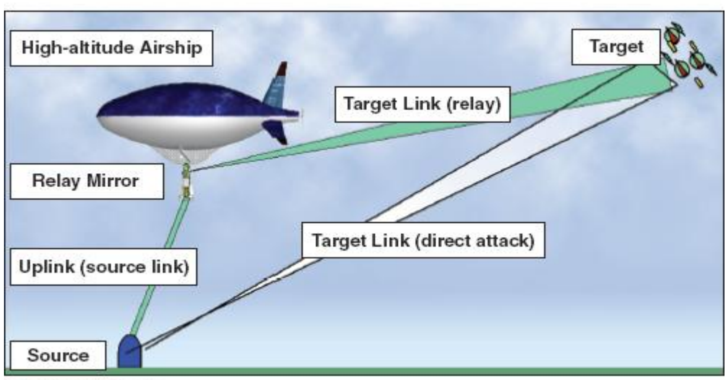

Figure 2. HAA RM system

Figure 4-6: Future depicted High Altitude Airship with laser relay mirror

According to the AFDEMP, the atmospheric systems are being developed in concert with the development of the High Altitude Airship (HAA) as the platform for the High Altitude Airship Relay Mirror System (HAARMS) (see Figure 4-6). The Army's Joint Land Attack Cruise Missile Elevated Netted Sensor (JLENS) is the platform for the Low Altitude Airship Relay Mirror System (LAARMS).[9] Sponsored by Air Force Space Command, the space-based, low

Earth orbit relay mirror, in accordance with the AFDEMP, is being explored to be part of the Near-Space Maneuvering Vehicle (NSMV).

The value relay mirrors provide is range extension and line of sight alternatives for LWS employment. By 2025, the air-based relay mirrors are expected to be in production and employed with LWS against tactical, operational and strategic targets on the surface, in the air and out in space. According to the AFDEMP, the low-Earth orbit space-based relay mirror is expected to have a production decision made by 2025. The value-added capability for air-based relay mirror systems is an extension of LWS range of up to 600km while space-based relay mirrors extend LWS as far as 10000km.[10]

Fire Control System Integration

Knowledge concerning beam pointing, atmospheric propagation and target tracking was gained through past operational experience with LELs used for target designation/illumination. The use of low-power lasers in HEL acquisition, tracking and pointing (ATP) experiments enabled parallel development of ATP technology with HEL device technology. Automatic Target Recognition (ATR) technology and Automatic Aimpoint Recognition (AAR) within future LWS fire control systems will provide essential decision-making information during targeting phases. The internal ATR/AAR technology coupled with the fire-control system of the sensor-shooter platform and, if required, off-board sensor-fused data could offer very timely targeting acceleration towards target engagement. The ATR/AAR technology, combined with speed of light weaponry, reduces the opportunity for escape of a fleeting or time sensitive target through automation expected to be faster than with a human in the loop (HITL).

2025 Laser Energy - More Than Just a Weapon

By 2025, military application of laser technology will exist in several forms requiring a wide range of power levels. With low to medium laser energy systems (LES), military application can come in many of the forms. **Low Energy Lasers** (LELs) usually emit far less than 100W of laser radiation and are used for ultra-high bandwidth communications, target designation, imaging, sensor and anti-sensor applications. Low power lasers are usually electric, diode or fiber lasers. **Intermediate power lasers** emit 300-3000W of laser radiation and are utilized for wide area and distant target area imaging. Current LESs are normally electric lasers.[11]

Boeing Corporation has demonstrated the ability of the Transformational Satellite Communications System (TSAT) to link from one satellite to another using a laser beam in a simulated space environment. The demonstration, performed in cooperation with Massachusetts Institute of Technology Lincoln Laboratories, was designed to provide operation at speeds of 40 gigabits per second.[12]

> Today, about 30 minutes of image data from a UAV would take 83 days to transmit over a 56 kilo-bit ISDN (digital phone) line, 3 days over a T1 line, or 15 minutes over the best transfer technology available. With a 1 gigabit-per-second laser communication line, data transfer would occur in real time. Verification, targeting and destruction would follow almost immediately. "With data transfers at 40 to 100 gigabits per second, multiple sensors could be combined in a single platform," says (Tony) Ruggiero. "A UAV could carry a synthetic aperture radar, signal intelligence, and video and all of them could be transmitting information at once to decision makers in command."[13]

Laser Radar (LADAR) is employed similar to millimeter wave radar, but uses laser beams to scan and process signals echoed from targets in order to create a virtual picture of the area. As the International Online Defense Magazine reports, "the LADAR processor looks for familiar patterns in the signals returned from targets. The LADAR seeker can detect objects and

identify specific features with very high definition of up to 15cm resolution from a distance of 1,000 meters…An Automatic Target Acquisition (ATA) algorithm continually processes the images to identify and acquire targets based on 3D templates preloaded into the weapon's memory before the mission. The process determines if priority targets are present in the area and gradually, a 3D image of the target is generated, to either reject or verify the target."[14] Technology utilizing LESs is being developed to enhance battlespace awareness. The purpose of these programs is to facilitate the location and identification of objects on the battlefield, to include those concealed by foliage, camouflage, structures or even underground.

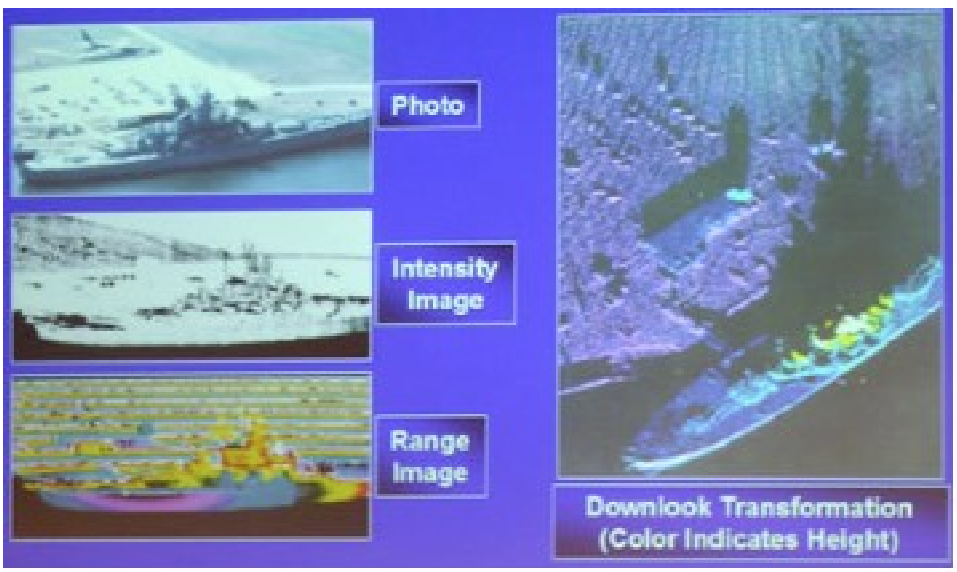

Figure 4-7: LADAR imagery[15]

Large Aircraft Protection

Other LES technologies being developed are designed for aircraft self-protection (both military and civilian) from IR missiles (air and surface launched). This first generation of Large Aircraft Infrared Countermeasures (LAIRCM) is operational on some large transport aircraft today. The development of active laser scanning techniques is enabling spiral upgrades to such systems as Directed Infrared Countermeasures (DIRCM) and LAIRCM resulting in a capability

to defeat IR missile threats. The tactical result allows larger transport aircraft and civilian aircraft some level of self-protection when operating in critical phases of flight (below 10K feet and takeoff & landing) when they are most susceptible to IR missile attack.

Conclusion

HELs emit several kilowatts through megawatts of laser radiation used for target destruction, degradation, disruption, denial, delay and deception. HELs are expected to offer joint forces the ability to instantaneously apply variable power levels of laser energy from tactically and strategically relevant distances. Some laser weapons may be employed non-lethally allowing for a wide range of options and opportunities to create effects and shape the OE. This instantaneous scalable application of laser energy is expected to induce and influence adversary behaviors and create outcomes not possible in today's OE.

Notes

1. Mark Neice, Director, High Energy Laser Joint Technology Office (DEF/JTO), presentation to Air War College Horizons 21 team, 6 September, 2006.
2. HQ USAF/XPXC, *2006 Air Force Directed Energy Master Plan Vol. I "Draft"*, (FOUO), information extract is unclassified.
3. Tom Burris, *Laser Strike Fighter*, presentation, slide 33. Proprietary Information Lockheed Martin Corporation.
4. Vago Muradian, "China's Mystery Satellites, U.S. Gauges Bejing's ASAT Strategy," Defense News.com, http://www.defensenews.com/story.php?F=2528099&C=thisweek (accessed 12 Feb 07).
5. Northrop Grumman, "Mobile Tactical High Energy Laser (MTHEL)," http://www.irconnect.com/noc/press/pages/news_releases.mhtml?d=63020, (accessed 12 Nov 06).
6. Vago Muradian , "China Attempted to Blind U.S. Satellite with Laser," DefenseNews.com, http://www.defensenews.com/story.php?F=2121111, (accessed 24 Jan 07).
7. Naval Postgraduate School Research, Directed Energy Research, "*Sponsor Highlight: Office of Naval Research*," U.S. Navy Quarterly Update, 15 May 2006, 3.
8. HQ USAF/XPXC, 32.
9.   Ibid, 35.
10. Ibid, 35.
11. Ibid, 37.

12. Boeing Corporation, “Boeing Laser Communications Demonstration Validates a Critical Element of TSAT,” Company Press Release, http://www.boeing.com/news/releases/2006/q3/060801a_nr.html (accessed 01-24-07).
13. Tony Ruggiero, “Laser Zaps Communication Bottleneck,” *Science & Technology Review* http://www.llnl.gov/str/December02/Ruggiero.html (accessed 24 Jan 07).
14. International Online Defense Magazine, “Laser Radar (LADAR) Guidance System,” *Defense Update*, http://www.defense-update.com/products/l/ladar.htm, (accessed 12 Dec 06).
15. Ibid

Chapter 5

Targeting with Lasers – How Do We Use Them?

> *Mere tonnage of explosives is a fallacious criterion. In the final analysis, victories are achieved because of the effect produced, not simply because of the effort expended.*
>
> **--BGen Haywood S. "Possum" Hansell, Jr., Memorandum to Army Air Force Chief of Staff General "Hap" Arnold, 26 July 1944**

Targeting plays a vital part in military operational employment. This chapter is the heart of the paper in that it attempts to frame how future LWS will relate to targeting, at the operational level, against targets in the OE of today. It then goes to the tactical level to describe the weaponeering involved with future LWSs. This chapter also includes the knowledge needed to capitalize on the unique characteristics of LWSs and how they enable advantages to be gained or maintained in the OE of 2025.

Targeting Defined

Targeting has been a vital part of air and space power since the first weapon was dropped from an aircraft. It has evolved over a century from a matter of primitive guesswork into a discipline based on scientific principles and robust processes used to guide employment of much more than just weapons dropped from airplanes. Targeting will continue to evolve as it assimilates the insights of effects-based operations, improvements in battlespace awareness, and other innovations. Even with evolution of warfare, targeting will still be central to the way the U.S. military conducts operations.[1] Through targeting, the assimilation of laser weapon systems

and the inherent capabilities they offer to shape the battlespace, in all phases of all operations, will be a complementary capability to achieve the Joint Force Commander's (JFC's) objectives.

"**Targeting**" is *the process for selecting and prioritizing targets and matching appropriate actions to those targets to create specific desired effects that achieve objectives, taking account of operational requirements and capabilities*.[2] Targeting involves intelligence, operational and planning functions and includes the use of kinetic or non-kinetic force by conventional or unconventional delivery means. LWS are a capability that should be operationally employed via targeting in the same manner as conventional weapons. In other words, the "process" of targeting shouldn't change for lasers. However, lasers produce unique effects which targeting should account for.

Targeting Basics

Joint and Air Force doctrine identically describe two types of targeting – Deliberate and Dynamic. "Deliberate Targeting" prosecutes targets that are known to exist in an operational area with actions scheduled against them to create effects desired to achieve JFC objectives. "Dynamic Targeting" (see Figure 5-1) prosecutes targets identified too late, or not selected for action in time to be included in the deliberate targeting process. An "effect" refers to a physical or psychological outcome which results from action. A target is a "thing" (person, facility, area, object, or function) upon which the effects are desired.

Capabilities Analysis is phase three within the Joint Targeting Cycle (see Figure 5-2). This phase compares and contrasts capabilities to target vulnerabilities, which involves estimating the effects of kinetic or non-kinetic, lethal or non-lethal attacks against specific, valid,

Figure 5-1: Dynamic Targeting[3]

prioritized targets. Weaponeering estimates, in this step, build upon the physical, functional or psychological vulnerability analysis which is performed in the target development phase. These estimates are then used to match targets to specific capabilities in order to produce desired effects. The other phases in the Deliberate Targeting process should remain similar with regard to present day weapon systems.

To determine LWS capabilities, the Laser Effects Test Facility (LETF) at Kirtland AFB, New Mexico, is analyzing the results of live laser fire tests to clearly define laser-target effects.

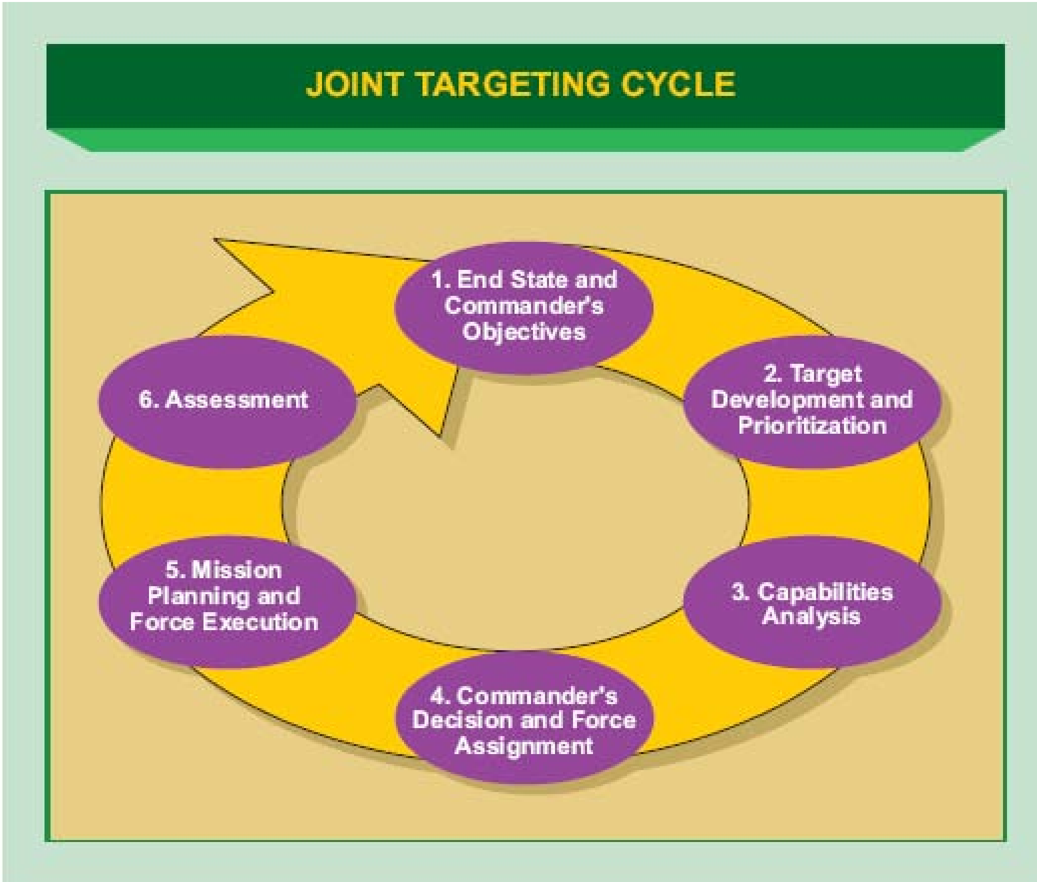

Figure 5-2: Joint Targeting Cycle[4]

The engineers and analysts at LETF use those results, aided with modeling and simulation, to assess various target sets. The accuracy of these live-fire results and the models created by the assessment will enable planners, weaponeers and operators to accurately grasp the capabilities of LWS in 2025.

Chapter 2 discussed the technological characteristics of laser weapon systems, i.e. what science and technology went into weaponizing laser energy. For LWS employment, there will be many physical and functional aspects to be evaluated in order to determine the LWS lethality against a specific target under certain operational conditions. This will be covered later in the chapter when weaponeering is discussed.

The correlation between Joint Targeting Steps 5 and 6 to Dynamic Targeting is vital to understanding the targeting processes in full. Dynamic Targeting is divided into six phases – Find, Fix, Track, Target, Engage, and Assess (F2T2EA) (see Figure 5-1). LWS by 2025 will greatly contribute to dynamic targeting phases because it will allow for the acceleration of F2T2EA, or the "kill chain," due to the speed and accuracy of LES and LWS systems. The phases of this process may be accomplished iteratively or in parallel. The find, fix, track and assess phases tend to be ISR-intensive, while the target and engage phases are typically labor-, force- and decision-making intensive.[5] "Emerging targets" is a term used to describe a detection that meets sufficient criteria to be developed as a potential target using dynamic targeting. The criticality and time sensitivity of an emerging target, and its probability of being a time-sensitive-target (TST), is initially undetermined. Emerging targets normally require further ISR and/or analysis to develop, confirm and continue dynamic targeting before subsequent TST classification.

The Kill Chain – Find, Fix, Track, Target, Engage, Assess (F2T2EA)

The following is an explanation of dynamic targeting using LWSs in current OE.

Find is the phase where *possible targets are detected and classified for further prosecution in the dynamic targeting process*. LADAR and LWS enable target detection and classification under foliage and detect changes in the environment for which present-day systems have limited capability. They can enhance intelligence collection plans based on the Joint Intelligence Preparation of the Operational Environment (JIPOE) using traditional and non-traditional ISR (NTISR), and may provide initial detection of emerging targets.

Fix is the phase where *a position is determined from terrestrial, electronic, or astronomical data*. LWSs, as "sensors," can be used both for both traditional and non-traditional

ISR, and are able to utilize low power laser energy actively to image or, by using LWS adaptive optics, to optically image an area passively in order to provide a fix on an emerging target.

Track is the phase *during which the target is observed and its movement monitored.* LWS can provide continuous tracking (active or passive) in order to maintain awareness on an emerging target. Due to the accuracy of LADAR and LWS, accurate target tracking/plotting of movement is further enabled with these future systems. Laser systems may also be coordinated or fused with laser communications to maintain situational awareness or track continuity with other sensors based on availability, operational requirements and environmental conditions.

Target is the *phase where the decision is made to engage the target in some manner to create the desired effects and the means to do so are selected and coordinated.* Beginning with target validation, an emerging target can be identified, classified and prioritized as a TST. Consequence of execution must be validated prior to moving ahead to the engage phase referencing Laws of Armed Conflict (LOAC), rules of engagement (ROE), no strike list (NSL), and restricted target lists (RTLs). Utilizing ATR and AAR technology, LWS could further enable kill chain compression by automating identification, classification and desired points of impact (DPI) for desired effects. Once validation of desired effects is completed, the target can be engaged by simply increasing the power out of a LWS.

Engage is the phase where *action is taken against the target*. At this point, LWS offer a unique capability in dynamic targeting – transitioning from sensor to shooter by simply increasing power output to create the desired lethality against the target. Any other weapon system, regarding the aspect of time, does not match this LWS sensor-shooter capability. Speed of light effects can immediately be applied to the target in this phase. This temporal advantage may allow the decision-maker(s) more time or simply to engage sooner.

Assess is the phase where *collection of information concerning the results of the engagement is conducted to determine whether the desired effects have been created.* LWS optics and low-power imaging enable immediate assessment of results allowing for expeditious re-attack to occur if needed.

Today's dynamic targeting process need not change, however. Scalable, speed of light effects from sensor-shooter platforms could compress the current kill chain sequence and reduce the adversary's time to contemplate, react or respond. Moreover, as ATR/AAR equipped LWS accelerate kill chain phases, the extra time gained through this acceleration could be applied towards risk assessment. As such, LWSs offer commanders discretion towards minimizing risk or utilizing temporal compression of the OE against the adversary, and this would appear to be an unchanged dynamic in 2025.

The operational phases of targeting allow for a macro-level approach to LWS application in the OE. A tactical level subset of targeting is weaponeering, which matches the weapon or weapon system to the target allowing for specified effects to be achieved. This allows for full application Effects Based Operations (EBO) methodology – connecting strategy to task – be implemented.

Weaponeering Defined

"**Weaponeering**" is *the process of determining the quantity of specific lethal or non-lethal weapon required to achieve a specific level of damage to a given target considering target vulnerability, weapons effects, munitions deliver accuracy, damage criteria, probability of kill and weapon reliability*.[6] A weaponeer is a professional tasked to objectively weigh the relative effects of different munitions and platforms against a specific target. The three pillars of weaponeering are target vulnerability, weapons characteristics and accuracy.

Target vulnerability is a quantitative measure of how susceptible a target is to a given weapon. This measure of susceptibility for conventional weapons uses damage criteria such as vulnerability to penetration, damage distances for blasts and lethal envelopes for fire. A weaponeer uses damage criteria indices for each conventional weapon that include mean area for effective blast (MAEB), effective fragmentation (MAEF) and building damage (MAEBldg). Since lasers don't blast, fragment or drop buildings, weaponeers will need new indices to enable them to assess, quantitatively, the vulnerability of a target to LWSs.

As previously discussed in Chapter 2, wavelength, power output (irradiance), and many other components of the laser affect the fluence delivered on the target. Recall that fluence, through thermal coupling on the target material surface, is the kill mechanism for a LWS. A given target and its various component materials will independently respond differently to laser

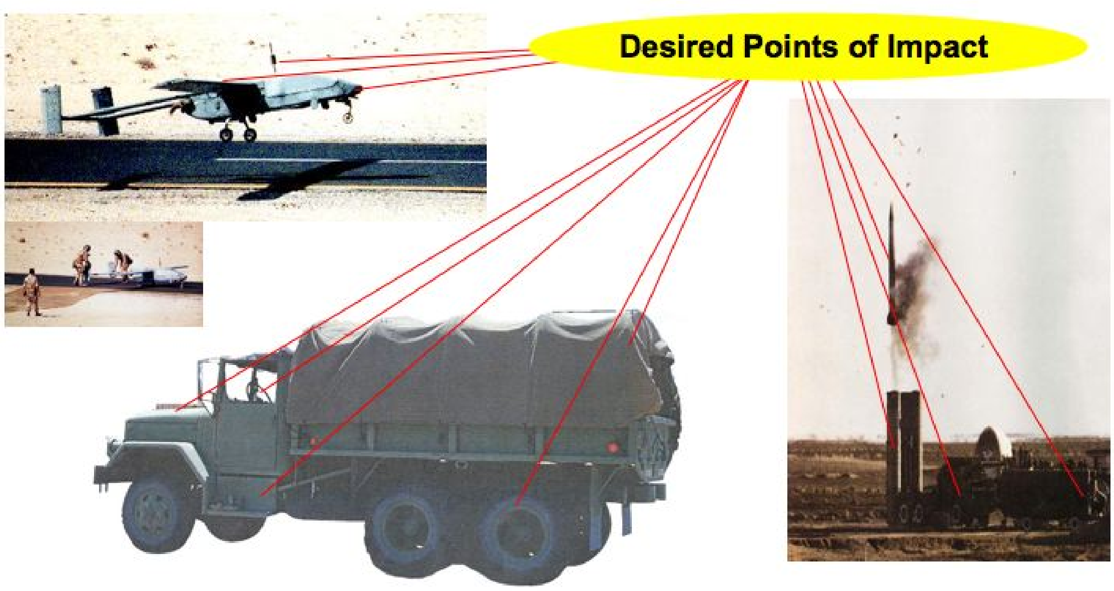

Figure 5-3: Failure Mode Analysis[7]

energy at target range (fluence). Accordingly, the tire on a vehicle may be less vulnerable to lasers than the metal engine block. However, the driver may be the most vulnerable of all components. As with weaponeering other weapons, failure mode analysis is part of assessing the target's vulnerability to a given weapon and thereby, assigns damage criteria for desired effects with a LWS (see Figure 5-3 & 5-4).

TARGET	POWER REQUIRED ON TARGET		
	LOW	MEDIUM	HIGH
Fighter Aircraft	Cockpit Fuel Tank		Flight Control Surface Electronics Failure
SAM (Solid)		Warhead Motorcase Guidance Control Failure	Flight Control Surface Radome
SAM (Liquid)	Fight Control Surface	Radome / Warhead Fuel / Oxidizer Tank Guidance Control Failure	
Cruise Missile (Low)	Fight Control Surface Warhead Fuel Tank	Guidance Control Failure	
Cruise Missile (High)	Radome / Warhead Fuel Tank		Fight Control Surface Guidance Control Failure
IADS SAM Radar & Support Structure			TET

Table 5-4: Example of Desired Point of Impact (DPI) lethality criteria[8]

Lasers are ultra-precise and can pin point small areas or components on a particular target. Test and evaluation sources should develop a database of laser-material responses in order to properly determine which target component(s) are most vulnerable to laser energy. This will aid in not only properly assigning LWS to specific targets, but further establishing damage criteria via the aimpoint on the vulnerable components of that target. Furthermore, this information can populate AAR database sub-systems to help establish quick aimpoint analysis of laser targets for rapid engagement.

Normally, a non-precision conventional weapon is weaponeered using *desired mean point of impact* (DMPI), an average place of impact to aim the weapon, or a group of weapons, on the target. Similar to precision-guided munitions, the ultra-precise capability of LWS should

use “desired point of impact” (DPI) as an exact place on a target. DPI selection aids in describing the desired result, selecting damage criteria, and the affect against the entire target system. Figure 5-4, provides an example of DPI selection and lethality criteria developed from component failure mode analysis.

Vulnerability of a target’s component material to laser energy, hazard distances and lethality envelopes should be included in the DPI assessment. Weapon to target effectiveness indices should remain standardized with other munitions as much as possible, but lasers will most likely have they own unique indices. Understanding laser weapon characteristics (discussed next) will further prepare targeting cells within operations centers to properly weaponeer LWSs using scalable laser energy against enemy targets.

Operational Characteristics of Laser Energy Weapons

Operational characteristics of LWSs as compared to conventional weapons will show a capability of tomorrow as compared to a capability of today. The expectation is that lasers will be capable of enhancing many operational functions (Counterair, Counterland, etc) and performing tactical missions (OCA/DCA, Air Interdiction, etc) from the air as well as from the ground. LWSs can create effects and achieve objectives at all levels – strategic, operational and tactical. The laser-unique characteristics are speed, ultra-precision, minimal collateral damage, scalability, and deep magazines. These unique weapon characteristics could offer increased latitude in target selection and less restriction, due to low collateral damage estimates and thereby increases the targets available to the joint force.

Speed is a significant strength for LWSs. Laser light travels (in a vacuum) at Mach 1,000,000 or 186,000 miles/sec, the speed of light. Today’s fastest air-air missiles are approximately Mach 4 (.78 miles/sec) and the latest surface-air missiles are roughly Mach 6

(1.28 miles/sec). However, when comparing missiles to lasers, assessing fluence at target range for the required dwell time should be included. Target engagement range must also be compared to the adversary's weapon engagement zone to assess risk to the LWS platform itself. Recall that power out, aperture size, spot size, beam quality all effect dwell time and/or range.

Example: JDAM Time of Fall at 14km (9miles) from 30,000 ft = 60 seconds (see Figure 5-5)

100Kw Laser Dwell Time: 400W/cm^2 at ~ 20km (12.4 miles) = 5 Sec dwell

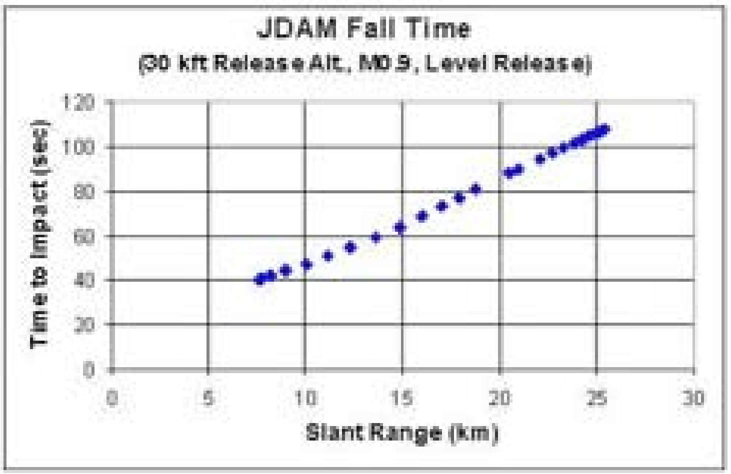

Table 5-5: JDAM Time of Fall[9]

One caveat is that lasers, as opposed to kinetic weapons, achieve different physical results. Therefore, desired effects should drive which weapon to use on which target. Against most moving or maneuvering targets a LWS is able to track pinpoint spots on target for duration of dwell time whereas most conventional weapons cannot.

The **magazine depth** of LWSs is a potential strength compared to conventional weapon systems. Chemical lasers are fuel limited due to the volume of chemical available for storage with the laser weapon system. This equates to approximately 20 shots with ABL.[10] Solid State Lasers are limited only by duty cycle for thermal dissipation. Therefore, SSL have virtually an unlimited magazine depth.

Laser weapon system **ultra-precision and pin-point accuracy** are strengths for LWSs. Current spot size can expect to be very small--small enough to selectively target a truck tire. Today a Laser Guided Bomb (LGB) has a reported accuracy of 10 meters or less.[11] A Joint Direct Attack Munition (JDAM) is accurate to 5 meters or less.[12] The newly developed Small Diameter Bomb (SDB) is 3 meters or less.[13] Precision munitions have created significant improvements in precise destruction of targets with low to minimal collateral effects. The ultra-precision of LWSs will enable more latitude on employment near or around a No Strike List (NSL) target because of minimal or no collateral effects. This will also reduce the Restricted Target List (RTL) and the surrounding area since LWS precision offers the ability to target an individual in a crowd that could be next to a restricted target. Secondary effects will still limit some application of LWS in close proximity to restricted or no-strike targets. For example, a weapons cache next to a religious site will cause damage, through secondary explosions, to the religious site.

Low to no **collateral damage** is one of laser weapon's greatest strengths. A LWS collateral hazard distance is estimated to be, at most, 75 meters.[14] This distance describes the laser energy scattering when employed against a reflective/refractive surface or environment. The effects of laser scattering are very different from the blast and fragmentation associated with kinetic weapons. As an illustration, Figure 5-6 shows the Risk Estimate Distances used in Close Air Support (CAS) for conventional kinetic weapons.

The **aerodynamic properties** of LWSs on aircraft tend to be low since they are carried

RISK-ESTIMATE DISTANCES			
Item	Description	Risk-Estimate Distance (meters)	
		10% PI	0.1% PI
Mk-82 LD/HD	500-lb Bomb/AIR	275	475
Mk-82 LGB[1]	GBU-12	75	200
Mk-83 LD/HD	1,000-lb/AIR	300	500
Mk-83 LGB[1]	GBU-16	75	200
Mk-83 JDAM[1]	GBU-31	100	250
Mk-84 LD/HD	2,000-lb/AIR	325	500
Mk-84 LGB[1]	GBU-10/24	75	225
Mk-84 JDAM[1]	GBU-32	100	225
Mk-20	Rockeye	225	650
CBU-87[2] CBU-89[2,3]	CEM or GATOR	275	425
WCMD[3]	CBU-87/89 w/kit	125	200
JSOW	BLU-97	125	225
2.75" Rockets	Rocket with various warheads (M151, M229, M261)	100	175
5" Rockets	Zuni with various warheads	150	200
Hellfire	AGM-114	50	75
M4, M12, SUU-23, M61, GAU-12, GPU-5A, GAU-8	20mm, 25mm, and 30mm Gatling Guns	100	150
AGM-65	Maverick (TV, IIR, Laser Guided)	25	75
AC-130[4]	25mm, 40mm	100	125
105mm Canon		80	200
WARNING **Risk-estimate distances are for combat use and are not minimum safe distances for peacetime training use.**			
RISK ESTIMATE DISTANCE NOTES [1] JDAM is a viable close air support munition, but detailed employment procedures need to be clearly estalished and understood. [2] Not recommended for use near troops in contact. [3] CBU-89 bombs are antitank and antipersonnel mines and are not recommended for use near troops in contact. [4] This distance is used for all AC-130 engagements as it has the largest fragmentation pattern for the largest weapon system on board.			

Table 5-6: Risk Estimate Distances[15]

internally. This nearly eliminates all parasite drag except for airflow disruption caused by extending the retractable turret into the air stream. This turret houses the laser-pointing device of the SSL expected on the Next Generation Gunship (NGG) and F-35. Today there are externally mounted munitions on most aircraft which increase drag coefficients and gross weight by significantly affecting the aerodynamic performance and fuel efficiency of the aircraft.

The **logistical footprint** of lasers is different depending on the type of laser, COIL or SSL. Chemical fuel for COIL lasers on aircraft and on ground-based lasers will require transportation and storage as a hazardous material. Security forces, maintenance personnel and technical/diagnostic personnel and equipment will be required for COILs. This logistical footprint is advertised by AFRL and LMC as minimal compared to conventional weapons. Depending on the consumption of chemicals, COIL systems could require large storage areas

and special loading equipment all within a secure storage facility/area. A SSL, in contrast, will have minimal or no storage requirements.

Austere environmental conditions of extreme heat would pose a significant challenge for LWS platforms that have complex, fragile optics and thermal-transfer systems. These require specialized equipment for diagnostics as well as replacements parts. The technical aspects required by maintenance personnel are unknown at this time, but, in the author's opinion, are anticipated to be as significant as any weapon system to date. In this light, logistical planning for LWSs appears to be in need of more detailed analysis for an accurate picture of the future.

LWSs have **scalable effects** based on power settings of the laser. They are capable of scaling from no-power optical imaging to low power non-lethal imaging and on up to full-power lethal laser energy with all variability in between. Results of LWS attacks may only be a small diameter hole (less than a foot), which may be hard to locate or validate depending on target location and the secondary effects. Adversaries might not be able to determine that a laser was the weapon that, in fact, carried out the attack. An example would be to not target the pilot of a fighter, but to target the engine intake with just enough laser fluence that it causes the intake wall to delaminate allowing debris to be sucked into the engine.

Atmospheric propagation is very important to delivering desired laser fluence at target range. **Environmental conditions** such as moisture (clouds, humidity, haze, fog, etc) cause diffraction (spreading of the laser energy beam/spot) that decreases fluence at target range. Lasers employment will be limited, or even prevented, based on certain weather conditions. Therefore, the Air Force Combat Climatology Center (AFCCC) and AFRL/DE should provide analytical tools for planners, targeteers/weaponeers and LWS operators that depict the environmental conditions specific for LWS employment parameters. Figures 5-7 through 5-10[16]

depict climatology for Iran using ceilings below 15,000 ft and visibility below 3 sm. Understanding and assessing regional climatology will be required before considering LWS employment in that region. The example depicts Iran during January or July and setting

Iran in the month of January

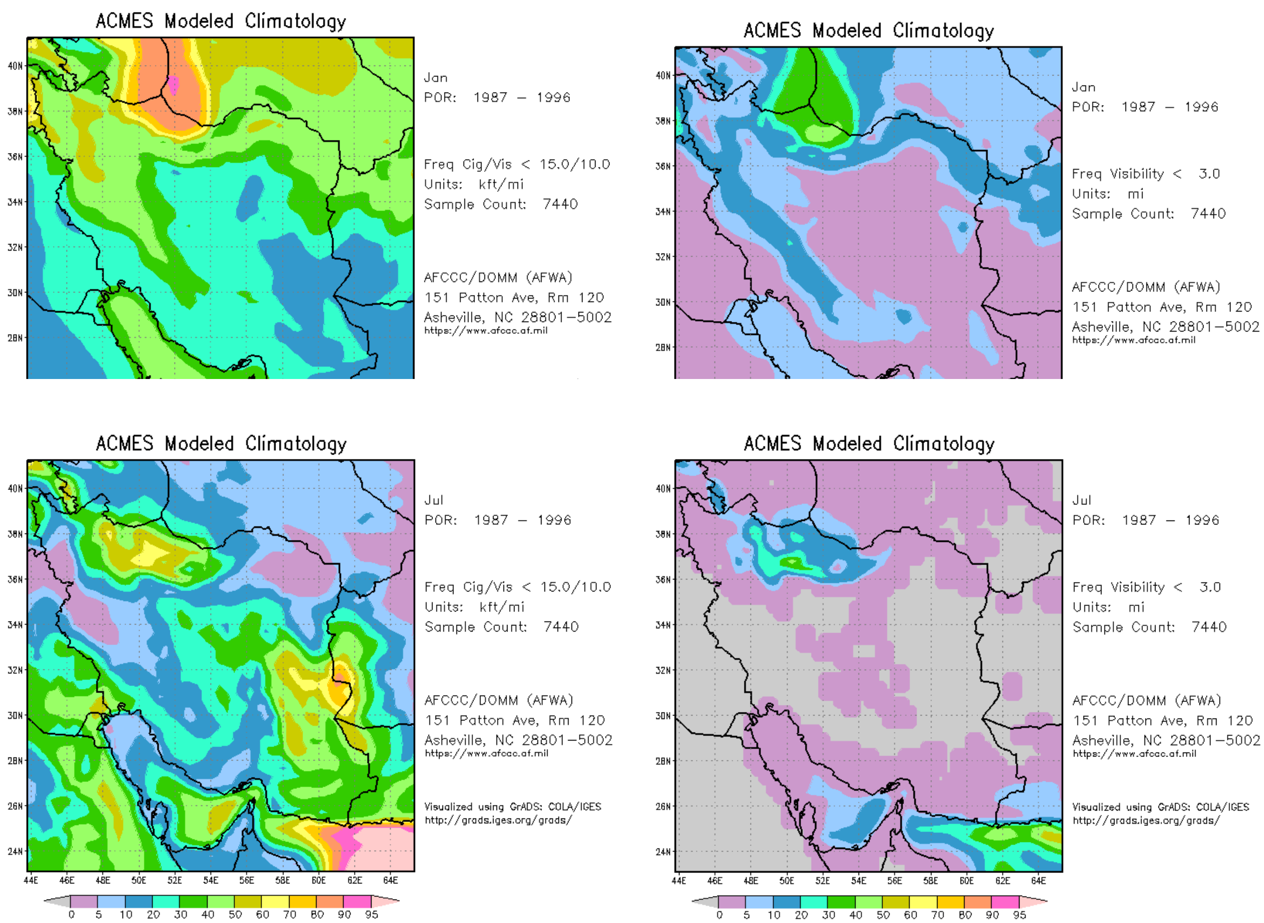

Figure 5-9: (left) - Ceilings below 15K and less than 10 miles horizontal surface visibility
Figure 5-10: (right) - Horizontal surface visibility of less than 3 miles

environmental criteria at 15,000 feet or less for ceilings and 3 miles or less visibility at the surface. Using these conditions for LWS employment criteria from a vertical/overhead position, the area around Tehran would be available 50-60% (due to ceilings) of the time in January and 40-50% (due to ceilings) of the time for July.

Lasers are not fire and forget weapons where a single LWS is capable of simultaneous engagement, or concurrent multi-targeting. The fire control system of a LWS should be able to step through targets sequentially, but must hold the laser spot on the DPI until desired lethality is achieved. Dwell time is affected by desired lethality and many previously mentioned variables, but will always decrease with range, assuming all other variables remain constant. In other words, the closer the target gets to the laser, the less time is required for the LWS to deliver fluence at target range. Therefore, FCSs should be capable of automatically and continuously updating required fluence at target range so the LWS dwells on a target only long enough to achieve desired lethality.

Lasers are **line of sight** (direct fire) weapons with no maneuvering photons and no effect of gravity on laser beam trajectory. It's just a straight line between the aperture and the DPI. This means the engagement of a target on the other side of a hill (or cloud) must wait until line of sight can be achieved. Therefore, LWSs employed against surface targets will most likely use look down shots via aircraft or relay mirrors. For air or space targets, clouds are primary inhibitors of line of sight. Consequently, the combination of line of sight with no fire and forget capability leaves the LWS platform vulnerable to detection and engagement throughout the dwell time.

LWS operators must understand the risks of shooting with friendlies or non-combatants near the **field of fire** as well as collateral effects in the near, side and far fields of view. Traditionally, this is based on the weapon engagement zone. With lasers, the same concept applies with the exception of the area beyond an air or space target. Laser energy isn't affected by gravity and won't succumb to gravitational effects if the beam does not hit its intended target. It continues on until absorbed. Aircraft, spacecraft and people beyond the target in the line/field

of fire can be at risk depending on their vulnerability to the delivered fluence at their range. Therefore, surface target prosecution may be the initial operating capability most likely to proceed since the air and space domains are non-limiting to laser energy flight paths.

Also, the field of fire will have implications on people in the proximity of laser energy weapon discharge. The British Medical Journal summarizes the risk lasers pose to the human eye with the following:

> The human eye is vulnerable for three reasons. Firstly, it is the only organ that allows optical radiation to penetrate deep within it. Secondly, the optical properties of the surface of the eye, the cornea, and to a lesser extent the lens increase the irradiance (power per unit area) in the passage of optical radiation between the cornea and retina by up to 500,000 times. Finally, the eye is consciously directed to any area of interest in the visual scene and thus presents the central and most sensitive area of the retina, the fovea, to the image of interest. If the fovea is destroyed the individual is legally registerable as blind, as he or she would have no high acuity vision. A single exposure to a rangefinder laser could destroy the fovea in 10^{-9} seconds…Originally, it was thought that the eye could be protected against laser systems by goggles. However, many laser devices switch wavelengths between pulses, so protective goggles would have to be opaque and are therefore self defeating. Blinding weapons have a huge psychological impact on troops. There is no treatment and, if the fovea is destroyed, then the individual is permanently blind in that eye.[17]

There is significant risk to aircrew eyes and optics/sensors on aircraft and satellites operating in a friendly laser environment. This is not to be confused with a laser threat environment where the intent of one side is to deliver blinding laser fluence into the eyes of the opponent. Fratricide is a challenge that must be addressed with future weapon system development, CONOPS, doctrine and tactics, techniques, and procedures (TTPs) to ensure space, air and surface friendlies are protected.

There are several vital sub-systems that are inherent to successful LWS performance. **Sub-systems performance** is vital because they ALL must be performing at the highest dependability in order for the laser to operate successfully. Therefore, the variability of all

systems is an intolerance and, by itself, a risk. This issue may, in fact, be considered one of the most significant challenges in LWS development.

Due to the linear/line of sight nature of LWS employment, the **geometry** of LWS to target is very important for reflection, refraction and scattering, but also for maintaining the laser spot on the DPI for the appropriate dwell time. For maneuvering targets, this problem becomes challenging if the orientation of the target changes and blocks the line of sight to the DPI. In some cases, the geometry may not be the target maneuvering, but the LWS platform orientation. In other cases, such as an urban environment, it may prove significant. “Where” the target is and “how” it is oriented towards the LWS could obstruct the line of sight to the DPI.

What is a Laser Target?

Initially, it may be useful to state what is *not* a laser target. Not all materials are vulnerable to laser energy. Targets that are made of concrete, underground, underwater, or in clouds are examples of non-laser targets. Lasers are inadequate for targeting deep underground bunkers, some bridges and reinforced concrete buildings if structural failure or total destruction is desired. However, communication lines, air intakes/exhausts or critical components may be vulnerable on such “non-laser targets.”

The concept of laser targets stems from the idea that thermal coupling with a material on the target will result in the desired effects. For example, ABL kills ballistic missiles by weakening a spot on the missile body during the boost phase of its trajectory that induces structural failure. Both Air Force Research Laboratory’s Directed Energy Directorate (AFRL/DE) and Lockheed Martin Corporation (LMC) have provided assessments of what determines a laser target. Tables 5-11 and 5-12 are examples of laser targets consolidated from AFRL/DE and LMC resources, identified with low, medium or high probability of laser energy vulnerability.[18]

Air & Space Targets

Target Vulnerability ⇒ Air & Space Target⇓	Low	Medium	High
Large transport aircraft			X
TBM, CM, UAV			X
Fighter/small aircraft		x	X
Surveillance aircraft			X
SAM, A-A missile			X
Satellite			X
ICBM		x	X

Table 5-11: Laser Air & Space Target Summary

Surface Targets

Target Vulnerability ⇒ Surface Target⇓	Low	Medium	High
Combat Vehicle		x	
Artillery System		x	
Dismounted Troops			X
Logistic site/Staging area		x	
Bridges/Tunnels	x		
Missile Launch site (CM/ICBM)		x	X
Command Center & HQ		x	
Fixed and mobile SAM, AAA, TBM site			X
Hardened artillery	x		
EW, GCI site			X
Supply route		x	
Boat, ship, barge & sub		x	X
Maritime LOCs		x	
Communication facility		x	
Power generation & distribution facility		x	
POL Storage facility		x	
Manufacturing facility		x	
Satellite launch & tracking site		x	
Parked aircraft			X
Sheltered aircraft	x		
Runway, taxiway	x		
Airfield support facility		x	X
Individual			X

Table 5-12: Laser Surface Target Summary

These targets are a sample of what LWSs will be capable of in the 2025 OE through non-kinetic scalable effects. As time moves forward to 2025, more targets and components in the OE will be realized as laser targets. It is currently estimated that laser targets comprise a minimum of 40% of the potential surface targets in the present-day conventional OE.[19] Further target analysis should reveal a higher percentage of laser susceptible targets in the air and space. Future target vulnerability analysis should better estimate the return the U.S. will gain by this capability in the OE of 2025 using present-day targets as the benchmark.

Weaponeering in the Future With LWS

Laser weapon systems are not technically munitions, but all effort should be made to standardize them. The Joint Munitions Effectiveness Manual Systems (JMEMS), updated via the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) are examples of munitions lexicon continuity that must include LWSs. Recently formed, the Directed Energy Test and Evaluation Capability (DETEC) organization is responsible for measuring the results and effectiveness of laser energy for ABL and ATL during their respective capability demonstrations. Through operational test and evaluation, DETEC should populate the database for laser effectiveness.

Weaponeering performed during contingency planning development at Combatant Commands (COCOMs) will significantly aid the deliberate/dynamic targeting process and plan execution. Therefore, it is important to develop this database from properly tested, modeled and simulated laser effects of nearly all targets within an expected enemy order of battle, identifying those that are laser "soft." The knowledge base for laser energy weapons will allow operation centers to properly leverage complementary capabilities between conventional and laser weapons in order to achieve the desired effects based on the commander's objectives.

Notes

1. AFDD 2-1.9, *Targeting*, 8 June 2006, ii.
2. Ibid, 1.
3. JP 3-60, *Joint Targeting*, 13 April 2007, II-14.
4. Ibid, II-3.
5. Ibid, II-12.
6. JP 1-02, *DOD Dictionary of Military and Associated Terms*, 12 April 2001, 583.
7. Dr. Larry Grimes, AFRL/DE, "Precise Lethal Effects to Difficult Targets," Science Advisory Board presentation, 28 Nov 06, slide 22.
8. Ibid, slide 23.
9. Tom Burris, LMC, "Laser Strike Fighter Unique Capabilities," presentation, slide 6.
10. Mark Farmer, "Dawn of the Airborne Laser," Popular Science, February 2003, http://www.popsci.com/popsci/printerfriendly/aviationspace/0d0a5b4a1db84010vgnvcm1000004eecbccdrcrd.html (accessed 12 Nov 2006).
11. Raytheon Corporation, "Paveway, Laser and GPS/Laser Precision Guided Bombs," http://www.raytheon.com/products/stellent/groups/public/documents/content/cms04_018951.pdf (accessed 02 Dec 2006).
12. "Factsheets: Joint Direct Attack Munition GBU 31/32/38," *Air Force Link*, United States Air Force, January 2006, http://www.af.mil/factsheets/factsheet.asp?fsID=108 (accessed 20 Nov 2006).
13. "Factsheets: GBU-39B, Small Diameter Bomb Weapon System," *Air Force Link*, United States Air Force, April 2006, http://www.af.mil/factsheets/factsheet.asp?fsID=4500 (accessed 20 No 2006).
14. Dr. Larry Grimes, AFRL/DE, "HEL Tutorial," presentation, 22 Apr 03, slide 34.
15. JP 3-09.3 *Joint Tactics, Techniques and Procedures for Close Air Support (CAS),* 3 September 2003, D-2.
16. From Michael Hunsucker, Air Force Combat Climatology Center, presentation of Analysis on regional climatology, 30 January 2006.
17. British Medical Journal, "Blinding Laser Weapons, Still available on the battlefield," (29 November 1997), http://www.bmj.com/cgi/content/full/315/7120/1392 (accessed 7 Feb 07).
18. Tom Burris, LMC, "Laser Target Summary," PowerPoint presentation, 07 Dec 06 and Dr. Larry Grimes, AFRL/DE, "HEL Tutorial," PPT brief, 22 Apr 03, slide 34.
19. Target estimation performed through analysis of target lists.

Chapter 6

Conclusions, Implications & Recommendations

> *You cannot escape the responsibility of tomorrow by evading it today.*
>
> **--Abraham Lincoln**

The idea that lasers will traverse the battlefield/space is not new. Those ideas were visions of futurists from the past. Today is that future and the scientific and military communities are very close to fielding the first operational laser weapon system--Airborne Laser (ABL). This chapter summarizes the previous chapters and offers conclusions and recommendations regarding the value of LWSs to the U.S. military and how they will be complementary to current capabilities. It closes by offering the author's visions and implications of using LWSs in the future OE.

Rapid technological change affects almost all organizations preparing for future challenges. Chapter 2 established one of the drivers of this rapid change as Moore's Law, which predicts an exponential change in a specific technology area. The expectation of rapid or accelerating technological change produces disruptive challenges for the U.S. military and makes the OE of the future less predictable in the near term. Directed energy, specifically lasers, as a disruptive challenge, has significant implications in future military operations. These implications are valuable to the U.S. military for meeting its security challenges in the OE of 2025.

Lasers are highly complex and require training and education in the specific science and technology that support them. Chapter 3 introduced and described basics of the electromagnetic

(EM) spectrum and the physics of laser energy--physics regarding laser energy as a waveform and why it is different than other types light. The chapter also described how laser energy interacts with material and physical characteristics and complexity of a laser system. It showed the many variables associated with a laser weapon system and how sub-system performance is critical for achieving lethality as it is weaponized for military use.

Laser energy weaponization is intuitive in today's technologically progressive society. Chapter 4 depicted technology programs associated with and depicted in the 2006 AFDEMP as well as other government laser programs. It discussed different laser weapon systems, sub-systems and associated enabling systems and the intent of their use in the future. The chapter also attempted to connect the science and technology from Chapter 3 with future laser weapon systems and how they will affect military operations in the OE of 2025.

As part of Effects Based Operations (EBO), targeting plays a vital role in military operations connecting strategy to tasks. Chapter 5 is the heart of the paper in that it attempted to frame how future LWSs will relate to targeting, at the operational level, against targets in the OE of today. It described weaponeering future LWSs against sample targets in today's OE the knowledge needed to capitalize on laser's unique characteristics and how they enable advantages to be gained or maintained in the OE of 2025.

Uncertainty in an Era of Change

Uncertainty is the defining characteristic of the future security environment. The U.S. can identify trends but cannot predict specific events. The 2005 National Defense Strategy acknowledges that although the U.S. military maintains considerable advantages in traditional forms of warfare, this realm is not the only, or even the most likely, one in which adversaries

will challenge the United States in the future.[1] Figure 6-1, visually depicts the expected challenges in a future of expected rapid technological change.

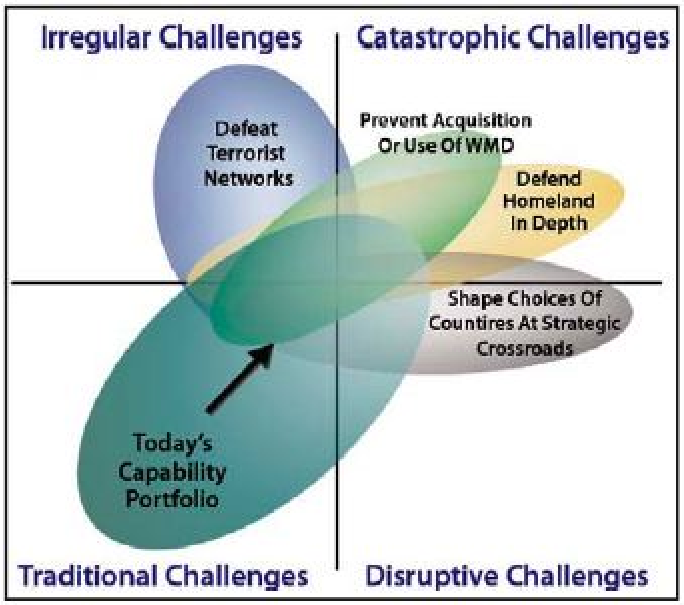

Figure 6-1: Future U.S. Security Challenges[2]

Conclusions

Laser energy weapon systems are capable of adding value to ensure success in the quadrants of irregular, catastrophic and disruptive security challenges. Traditional challenges are most often associated with states in conventional military competition. In this arena, temporal and spatial compression due to the speed and magazine depth of LWSs are valuable enablers that can create a tempo of operations which can overwhelm an opponent. LWS and conventional weapon systems in concert can complement each other through kill chain compression while expanding the targets available to affect the opponent.

The U.S. military has increasingly become dependant on precision weapons against both traditional and irregular challenges.[3] LWS accuracy will allow for the Joint Force to target very specifically with minimal collateral damage. This **ultra-precision engagement capability** will permit the targeting of specific components or persons with a spot of laser energy less than 1 foot

in diameter.[4] Such accuracy will **reduce the hazard area surrounding restricted or no-strike targets** allowing for more latitude in the proximity of delivery effects, particularly in urban areas where irregular threats seek sanctuary. This offers a benefit that can be held and used as a surprise or used to collapse an opponent's ability to hide or retreat. It is the author's opinion that the innovation from such accuracy will open new ways to study and counter both traditional and irregular challenges.

With respect to catastrophic challenges, it is worth noting that the initial thrust of LWSs was to defend against ballistic missile threats. In the 1980's, President Ronald Reagan initiated the Strategic Defense Initiative (SDI), which was designed to use, among other capabilities, space-based laser weapons against Intercontinental Ballistic Missiles (ICBM) launched by the Soviets.[4] Today, as part of the MDA, ABL is the laser weapon capability being developed to counter the threat of ballistic missiles from North Korea and other actors that threaten the U.S.. The idea that began as a counter to threats in the past was renovated to meet the challenge of threats today. But today it is not just one type of challenge or one type of threat that is independently employed; it is multiple challenges innovatively combined.

Indeed, recent experience indicates the most dangerous circumstances arise when the U.S. faces a complex set of challenges. For example, adversaries in Iraq and Afghanistan present both traditional *and* irregular challenges. Terrorist groups like al Qaeda are *irregular* threats but also actively seek *catastrophic* capabilities. North Korea at once poses traditional, irregular and catastrophic challenges. Finally, in the future, the capable opponents may seek to combine truly *disruptive* capacity with *traditional*, *irregular* or *catastrophic* forms of warfare.[2]

Laser energy has advantages over bullets, bombs or missiles in addressing mixed challenge categories because its characteristics differentiate it from other weaponry based on

speed, precision, magazine depth and low collateral effects. It offers the U.S. military asymmetric offensive and defensive advantages in controlling the air, space and maritime domains in the future OE while maintaining deterrent qualities, particularly if enabled by an air platform that can make the LWS omnipresent. Such a capability can deter disruptive challengers. For all of these reasons, the continued pursuit of directed energy weapons, specifically laser weapons, should continue.

Implications: New Ways of Targeting

Temporal Compression Targeting

The speed at which a LWS can deliver effects combined with the deep magazine of solid-state lasers (limited only by 25% duty cycle), against laser "soft" targets is significant. Targets available for prosecution can be cycled through in an exceptionally short time frame.

Example: 10s dwell time to deliver desired effects on the target component

10 LWS platforms available for tasking,

250 laser "soft" targets, with 4 DPIs each (1000 DPIs total)

Average 2 DPIs per minute/LWS platform = 20 total DPIs/min

1000/20 = 500 min = 8.33 hours

Remember, this is theoretical math and NOT operational reality and therefore doesn't take into account many other variables, including how this would affect the battle rhythm of the entire joint force.

Just in Time Targeting

In order to reduce costs, today's modern business and governmental practices have reduced inventories (replacement parts) to minimal levels, utilizing just-in-time logistics (JITL) and supply chain management. This creates a vulnerability for the U.S., as well as most

opponents. JIPOE should reveal the orders of battle for an opponent revealing groups of targets (20 x MiG-29, 300 x tank, 100 x SAM, etc). These groups are uniformly at risk by now having the same component destroyed (engine, tire, tread, nose cone, etc). Laser weapon system's ultra-precise accuracy allows for DPI selection that is unprecedented in modern warfare. Multiple LWSs, tasked with the same DPI (target component) on the same target type, could create a logistical ripple effect that would render the numerous targets impotent until replacement parts could be purchased and delivered.

Example: JFC objective: Establish Air Superiority

100 known SAM sites within a nation's Integrated Air Defense Systems

4 system components required for acquiring, tracking and firing of SAM

1000 total missiles located with the 100 SAM sites. Using the previous example.

Combine JIT Targeting with Temporal Compression Targeting

Targeting – 400 common system components to create JITL log jam

1000 missiles to prevent ballistic employment (shoot w/no radar)

1400 DPIs, 10 LWS on LO platforms at 2 DPIs/min

700 minutes or 11.7 hours

This targeting method would offer the JFC a unique opportunity to create the effects desired (Air Superiority) while allowing for the reconstruction and reconstitution costs of that nation to be greatly reduced. In other words, the re-establishment of a defensive force would be less expensive if only components had to be replaced instead of replacing the entire weapon system.

Urban Geometry Targeting

Many advocates have expressed the value of laser effects in an urban environment. The questions to ask are how vertically developed and how populated is the urban environment.

Substantial vertical development will preclude long horizontal look angles and will force “line of sight only” laser platforms to a more vertical look angle depending on surrounding buildings. If future conflicts are expected to be increasingly in urban settings, then understanding the capabilities and limitations of LWS will be valuable.

Chapter 2’s discussion on angle of incidence, reflection and refraction will impact LWS employment (see Figure 6-2). LWS utility in low vertically developed urban areas (average 3 storey buildings or less) will pose little problem for laterally displaced LWS employing against

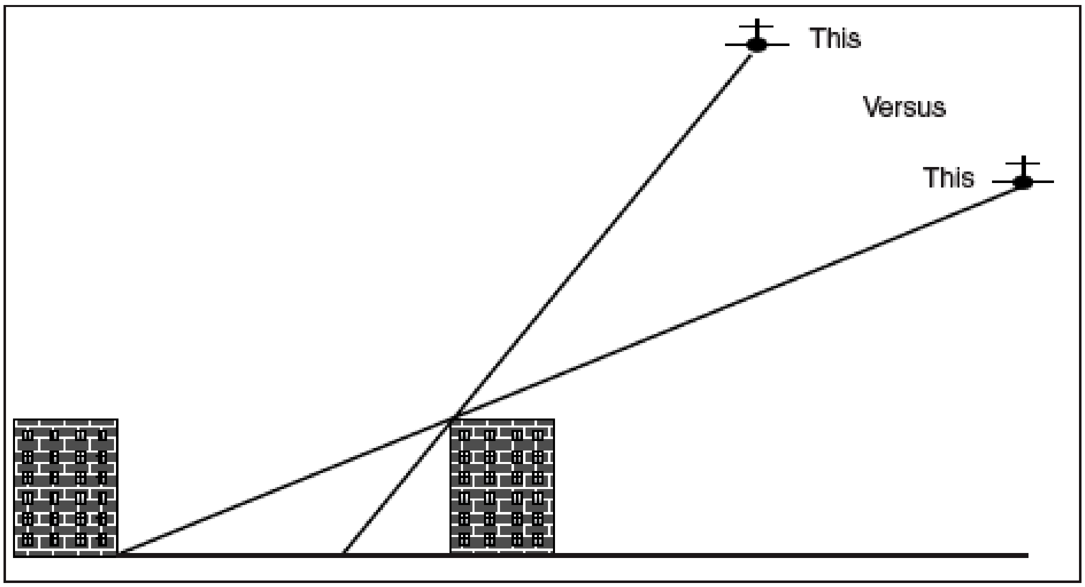

Figure 6-2: Urban Geometry – Line of Sight Angle[3]

standoff with targets possibly unaware that the LWS is actually capable of targeting them, especially in, or on top of, the building. For a more vertically developed urban area (average 4 storey buildings and up), it will be necessary for the LWS to fly much closer laterally, possibly even overhead the target environment, to obtain line of sight targeting.

The opportunity to employ against a target in a building (such as a sniper) *in this setting* is very low due to the angles of incidence the LWS will have with line of sight and reflection

from any glass around the target (see Figure 6-2). The resulting capability improvements, just in targeting processes, are only one aspect to consider. To enable the utility of LWS in both Deliberate and Dynamic targeting, the joint force J2 needs to ensure weaponeers populate target folders with pre-weaponeered LWS assessments. Pre-weaponeering for LWS also dramatically improves the options the JFC has for delivery effects of kinetic, lethal or non-lethal force against various targets. The process of weaponeering defines the force application, identifies the relationship of given weapon's effectiveness against target damage criteria and defines the delivery accuracy and collateral damage assessment. Weaponeering is a vital element to this targeting process.

<u>No Fly Zones enforced by GBL and HAARMS</u>

Over 12 years were spent patrolling the Northern and Southern No-Fly Zones of Iraq following Operation DESERT STORM. These operational commitments consumed countless flight hours on almost all Combat Air Force platforms as well as Command, Control and ISR assets. Flight crews spent extraordinary amounts of time flying sorties to enforce this effort. Whether that flight time was a valuable means to achieve the operational objectives is a valid question. Consider an alternative: two 1-megawatt High Energy Laser Weapon Systems (HELWS) with three relay mirrors (see Figure 6-3) as a substitute for a large proportion of the sorties flown in Operations NORTHERN and SOUTHERN WATCH.

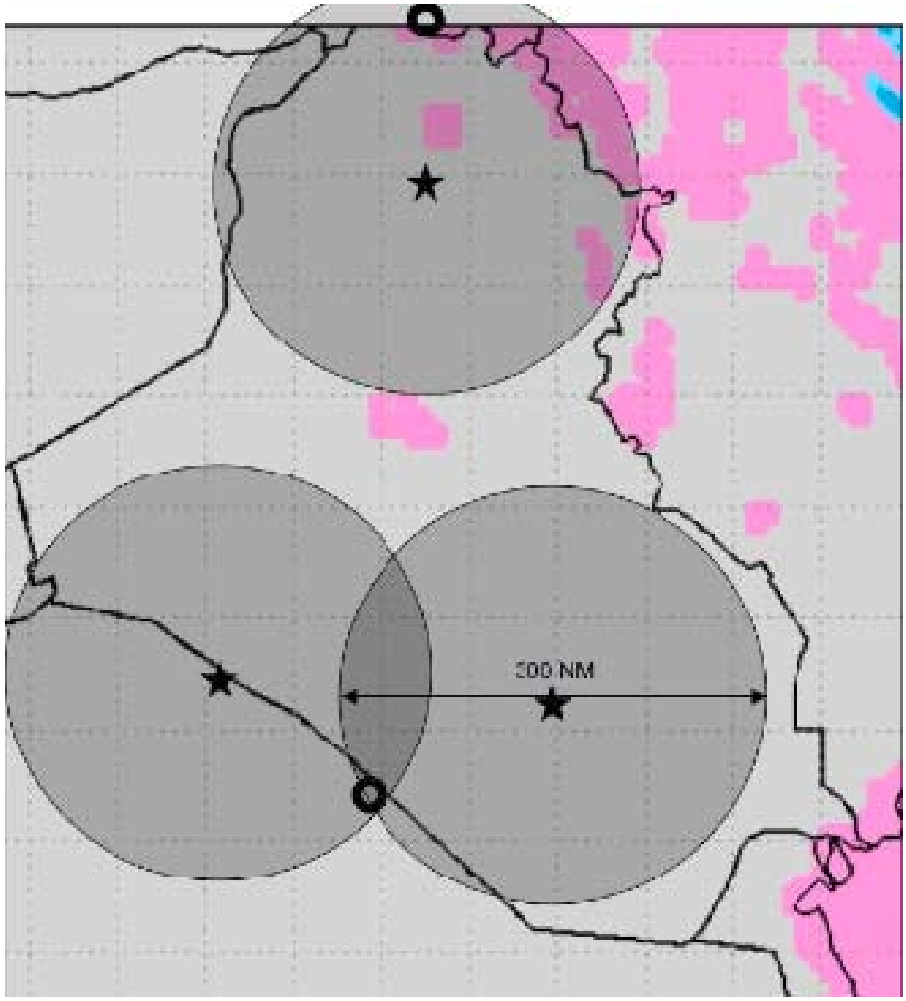

Figure 6-3: No Fly Zone enforced by GBL and HAARMS

★ = HAARMS (High Altitude Airborne Relay Mirror System)

○ = 1MW Mobile GBL or ABL

Presence would be needed to cover for occasional maintenance or weather days when the GBL/ABL or relay mirrors needed servicing. However, many aircraft flight hours (i.e. life cycles) were used up in this endeavor. This could be a future alternative for No-Fly Zone operations.

Recommendations

Two ideas were argued in this paper. Are laser weapons a sustaining or disruptive technology? How would we use this technology in 2025? Harvard Professor, Clayton Christensen, states that large companies have certain barriers to innovation which make it difficult to invest in disruptive technologies early on. In other words, large legacy organizations have set ways in approaching new technologies. Baggage from precedents (such as equipment, training, procedures) hinders a quick response to disruptive technologies. Therefore, the culture of the DOD will need to shift toward less rigid paradigms in the way to approach technology problems. In that light, allowing for innovation also requires allowing for failure. "Discovering markets for emerging technologies inherently involves failure, and most individual decision makers find it very difficult to risk backing a project that might fail because the market is not there."[5]

Capability assumptions for this paper came from the *Draft* 2006 Air Force Directed Energy Master Plan (AFDEMP). Within the AFDEMP is the AF DE Roadmap (AFDER). The justification of using a draft was that it had been vetted by AFRL and the Air Staff, but not yet signed by the AF Chief of Staff. The capabilities being developed as part of the AFDER were used in expressing Chapter 4, *Laser Capabilities – Now to 2025*. This paper *did not* attempt to argue or validate these capabilities and their efficacy; it simply made an attempt to express how the U.S. would or should use these capabilities in the future.

Recommendation 1: <u>Advanced Technology Capabilities Demonstrations (ATCD) should be accelerated to the fullest extent financially feasible</u>. This means rapid progression for ABL and ATL. Furthermore, increased funding for research & development for promising future laser weapon systems that spin off of these ATCDs. As the ATCDs prove or disprove

laser weapon system utility and worth, DOD decision-makers should have a pre-programmed, pre-segmented roadmap for developing the most promising capabilities in order to continue a rapid path to IOC. It is the authors' opinion that those promising capabilities for the Air Force will be the Advanced Tactical Laser (ATL), Laser Strike Fighter (F-35 laser variant) and the high and low altitude relay mirrors. For joint technology development, the mobile ground based laser (GBL) will add value with the relay mirror systems toward conducting many offensive and defensive mission areas against surface, air and space targets. ABL is a niche weapon system and unless the DOD decision-makers are willing to re-role it to other mission areas, it should remain as currently funded at seven aircraft.

Recommendation 2: Accelerate the testing by the AFRL laser test facility to determine the effects of lasers against specific materials. AFRL/DE should build a database of laser-material effects based on targeting and weaponeering parameters that areas similar as possible to those in use for current weapons. Concurrently fund the DARPA programs for automatic target recognition and establish one for auto aimpoint recognition to simultaneously populate the databases for future LWS. Standardize the laser lexicon across all of DOD with specific terminology and effects currently used with the Joint Munitions Effectiveness Manual Systems (JMEMS) and validate with the Joint Technical Coordinating Group for Munitions Effectiveness.

Recommendation 3: Presently, it is estimated that 40% (minimum) of the surface targets in a given theater are laser susceptible targets. This is a rough estimate and should be validated with a thorough study. This laser susceptible target study should occur by two separate Air Force organizations, one academic and the other operational, and a third independent body. The AF organizations should look at specific target sets in separate areas of responsibility. The independent organization should be a non-governmental, non-defense contractor body to assess

the value of how many laser targets truly exist in a given scenario. The author recommends the J2 for Korea or U.S. Pacific Command should analyze one AOR and a group from Air University should examine another AOR. The independent organization, such as RAND, should pull information from the Defense Contractors: Boeing, Lockheed Martin and Northrop Grumman, as well as the two AF organizational studies to compile a comprehensive feedback on all assessments.

Recommendation 4: Enable the geographic Combatant Commands to weaponeer laser susceptible targets in order to build up target folders with laser solutions, using current applications that will allow for proper target development. This pre-execution work will allow the planning and execution across the full range of military operations to be more adaptable to changing conditions. The scalability of LWS employment will allow for non-lethal deterrence as an option to shape the security environment of the region. It will also pre-condition the planners to consider the laser weapon employment alternative, as well as send a clear message to opponents that laser energy is an option for prosecution of targets.

Recommendation 5: Assign the Air Force Combat Climatology Center (AFCCC) and Air Force Research Laboratory, Directed Energy Directorate (AFRL/DE) to continue climatology analysis by depicting environmental limitations regarding LWS employment. This analysis should be geared toward covering the geographic Combatant Command areas of responsibility, and ultimately handed off to the COCOMs for future operational planning. Also, standardized weather products specifically for LWS planners and operators similar to those used for night vision devices and Infrared sensors should be developed.

Recommendation 6: The ultimate advantage of the U.S. military, according to the 2006 QDR, is “superbly trained, equipped, and highly dedicated people.” Therefore, continuing to

invest in the recruitment, development and career progression of the people serving in DOD should be an ongoing focus for the future. One of the limitations, in the author's opinion, is DOD's innovative stagnation. The U.S. military tends to be very rigid, procedure-dependent and inflexible when it comes to change or creative problem solving. The environment for innovative thinking is stifled. Leaders of the U.S. military should understand that being able to improvise, adapt and overcome is going to be a critical skill set for success in the future OE if it is truly going to experience accelerating change. Therefore, <u>educate and train the combat forces how to innovatively solve an operational problem or problems within their specialty and outside of it</u>.

Recommendation 7: Air Combat Command, Air Warfare Center, AF Space Command and Air Armament Center, should <u>begin developing laser weapon CONOPS.</u> These organizations should formulate the initial training on laser weapon systems to start the cultural infusion and public relations campaign of operationalizing the "laser as a weapon" idea to the Air Force, sister services, DOD and the public. The Air Force should create an environment that fosters creative solutions for DE ideas, employment and follow-on development.

Recommendation 8: <u>Adjust the technology development-acquisition process</u> to accommodate the expected rapid technological change rate. This will, in turn, provide the users of these systems a weapon that is not currently countered or, worse still, obsolete when it is presented to them at the initial operating capability date. This is such a large-scale recommendation it will be better left in the aforementioned broad terms.

Knowing that the future security environment is uncertain is the initial step to preparing for it. The U.S. military has echoed this as fact through its strategy documents and quad chart describing the future OE challenges. Challenges that are part of this environment include laser weapons. These speed-of-light, ultra-precise, low collateral damage weapons are part of the

disruptive challenges in this uncertain future security environment and capitalizing on them will enable the U.S. to retain a military advantage in the future. Laser weapon systems can’t solve every problem, but their development will give the U.S. a lead and help prepare for any adversaries that might also be developing this disruptive technology.

Notes

1. Summarized from *The National Military Strategy of the United States of America*, 2004, iv.
2. Ibid.
3. Precision weapons accounted for only 9% of the munitions expended in Operation DESERT STORM, 29% in Operation ALLIED FORCE and 60% in Operation ENDURING FREEDOM. Benjamin S. Lambeth, *Air Power Against Terror, America’s Conduct of Operation Enduring Freedom*. Santa Monica, California. RAND Corporation, National Defense Institute. 2006.
4. Dr. Larry Grimes, AFRL/DE, “HEL Tutorial,” presentation, 22 Apr 03, slide 34.
5. Ashton B. Carter, *Directed Energy Missile Defense in Space–A Background Paper* (Washington, D. C.: U.S. Congress, Office of Technology Assessment, OTA-BP-ISC-26, April 1984), 3.
6. Alan J. Vick, John Stillion, David R. Frelinger, Joel Kvitky, Benjamin S. Lambeth, Jefferson P. Marquis, Matthew Waxman, RAND Project AIR FORCE., *Aerospace Operations in Urban Environments*, 2000, 99.
7. Clayton M. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Boston, Mass.: Harvard Business School Press, 1997, 34.

Bibliography

British Medical Journal, “Blinding Laser Weapons, Still available on the battlefield,” (29 November 1997), http://www.bmj.com/cgi/content/full/315/7120/1392 (accessed 7 February 2007).

Boeing Corporation, “Boeing Laser Communications Demonstration Validates a Critical Element of TSAT,” Company Press Release, http://www.boeing.com/news/releases/2006/q3/060801a_nr.html (accessed 24 January 2007).

Burris, Tom. Lockheed Martin, *Laser Strike Fighter*. 17 October 2006 and “Laser Strike Fighter Unique Capabilities,” PowerPoint brief, proprietary information.

Carter, Ashton B. *Directed Energy Missile Defense in Space–A Background Paper* (Washington, D. C.: U.S. Congress, Office of Technology Assessment, OTA-BP-ISC-26, April 1984).

Christensen, Clayton M. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Boston, Mass.: Harvard Business School Press, 1997.

Columbia University, “Laser Machining Process,” http://www.mrl.columbia.edu/ntm/level1/ch03/html/l1c03s03.html (accessed 02 December 2006).

Dubash, Manek “Gordon Moore speaks out,” *Techworld*, 15 April 2005, http://www.techworld.com/opsys/features/index.cfm?featureid=1353&pagtype=samechan&categoryid=2 (accessed 26 November 2006).

Department of Defense, *The National Defense Strategy of The United States of America*, March 2005.

Department of Defense, *Quadrennial Defense Review Report*, February 6, 2006.

Department of Defense, *Joint Vision 2020*, June 2000.

Dvorak, John C. “The Myth of Disruptive Technology,” *PCMAG.COM*, 17 Aug 2004, http://www.pcmag.com/article2/0,1759,1628049,00.asp (accessed 26 November 2006).

DARPA. “*2006 DARPA Fact File*: A Compendium of Programs”, Defense Advanced Research Projects Agency, June 2006.

Defense Science Board Task Force, HIGH ENERGY LASER WEAPON SYSTEMS APPLICATIONS, June 2001.

“Factsheets: F-22A Raptor,” *Air Force Link*, United States Air Force, June 2006, http://www.af.mil/factsheets/factsheet.asp?id=199 (accessed 4 December 2006).

"Factsheets: Joint Direct Attack Munition GBU 31/32/38," *Air Force Link*, United States Air Force, January 2006, http://www.af.mil/factsheets/factsheet.asp?fsID=108 (accessed 20 November 2006).

"Factsheets: GBU-39B, Small Diameter Bomb Weapon System," *Air Force Link*, United States Air Force, April 2006, http://www.af.mil/factsheets/factsheet.asp?fsID=4500 (accessed 20 November 2006).

Farmer, Mark "Dawn of the Airborne Laser," Popular Science, February 2003, http://www. popsci.com/popsci/printerfriendly/aviationspace/0d0a5b4a1db84010vgnvcm1000004eecbccdrcrd.html (accessed 12 November 2006).

Grimes, Dr. Larry, AFRL/DE, "HEL Tutorial," PowerPoint brief, 22 April 2003.

Grimes, Dr. Larry, "Precise Lethal Effects to Difficult Targets," SAB PPT brief, 28 November 2006.

Headquarters USAF/XPXC, *2006 Air Force Directed Energy Master Plan (Draft)*. AF Pentagon, Washington DC. 2006.

Headquarters Air Force Doctrine Center. *Air Force Doctrine Document 2-1.9, Targeting.* Maxwell AFB, AL. 2006.

Headquarters Air Force Doctrine Center. *Air Force Doctrine Document 2*, *Operations and Organization*. Maxwell AFB, AL. 2006.

Hunsucker, Michael, Air Force Combat Climatology Center, PowerPoint Analysis on regional climatology, 30 January 2006.

Intel Corporation, "Moore's Law Timeline," ftp://download.intel.com/pressroom/kits/ events/ moores_law_40th/MLTimeline.pdf (accessed 11 February 2007).

International Online Defense Magazine, "Laser Radar (LADAR) Guidance System," *Defense Update*, http://www.defense-update.com/products/l/ladar.htm, (accessed 12 December 2006).

Joint Forces Command, *JP 1-02, DOD Dictionary of Military and Associated Terms*, 12 April 2001.

Joint Forces Command, *JP 3-09.3, Joint Tactics, Techniques and Procedures for Close Air Support (CAS)*, 3 September 2003.

Joint Forces Command, *JP 3-60, Joint Targeting*, 13 April 2007.

Joint Forces Command, *Joint Operational Environment, 2030 and beyond*, 2006.

Lambeth, Benjamin S. *Air Power Against Terror, America's Conduct of Operation Enduring Freedom*. Santa Monica, California. RAND Corporation, National Defense Institute. 2006

Lightsources.org, "What is a Light Source?" http://lightsources.org/cms/?pid=1000166, (accessed 30 November 2006).

Moore, Gordon "Cramming more components onto integrated circuits," *Electronics* 38, no. 8 (April 19, 1965), Intel Corporation website, ftp://download.intel.com/museum/Moores_Law/ Articles-Press_Releases/Gordon_Moore_1965_Article.pdf (accessed 11 February 2007)

Muradian, Vago "China's Mystery Satellites, U.S. Gauges Bejing's ASAT Strategy," Defense News.com, http://www.defensenews.com/story.php?F=2528099&C=thisweek (accessed 12 February 2007)

Muradian, Vago "China Attempted to Blind U.S. Satellite with Laser," DefenseNews.com, http://www.defensenews.com/story.php?F=2121111, (accessed 24 January 2007)

NASA Goodard Space Flight Center, "Measuring the electromagnetic spectrum," http://imagine. gsfc.nasa.gov/docs/science/know_l1/emspectrum.html/ (accessed 15 December 2006)

National Academy of Sciences Committee on Defense Intelligence Agency Technology Forecasts and Reviews, *Avoiding Surprise in an Era of Global technology Advances*, ISBN 0-309-54916-7, (Washington D.C. National Academy Press, 2005).

Naval Postgraduate School Research, "Directed Energy Research," *Sponsor Highlight: Office of Naval Research*," U.S. Navy Quarterly Update, 15 May 2006.

Northrop Grumman, "Mobile Tactical High Energy Laser (MTHEL)," http://www.northrop grumman.com/missiledefense/ProgramInfo/MTHEL.html, (accessed 12 November 2006).

Neice, Mark. DEF/JTO (Director, High Energy Laser Joint Technology Office), JTO PowerPoint Brief to AWC Horizon's 21, 06 September 2006.

Raytheon Corporation, "Paveway, Laser and GPS/Laser Precision Guided Bombs," http://www.raytheon.com/products/stellent/groups/public/documents/content/cms04_018951.pdf (accessed 02 December 2006).

Rizer, Col Ken "Alternate Futures for 2025: A Mid-course Update" (Air War College, Blue Horizon's Future Study), 2006.

Ruggiero, Tony " Laser Zaps Communication Bottleneck," *Science & Technology Review* http://www.llnl.gov/str/December02/Ruggiero.html, (accessed 24 January 2007).

Shore Laser, "More About Lasers," http://www.shorelaser.com/AboutLasersDet.html, (accessed 30 November 2006).

Wolfram Research, “Angle of Incidence,” http://scienceworld.wolfram.com/physics/Angleof Incidence.html (accessed 02 December 2006).

Wolfram Research, “Angle of Reflection,” http://scienceworld.wolfram.com/physics/Angleof Reflection.html (accessed 02 December 2006).

Wolfram Research, “Angle of Refraction,” http://scienceworld.wolfram.com/physics/Angleof Refraction.html (accessed 02 December 2006).

Vick, Alan J., John Stillion, David R. Frelinger, Joel Kvitky, Benjamin S. Lambeth, Jefferson P. Marquis, Matthew Waxman, *Aerospace Operations in Urban Environments*, RAND Project AIR FORCE, 2000.

Bibliography not cited

Dunn, Richard J, III. *Operational Implications of Laser Weapons*, Northrop Grumman, analysis center, September 2005.

Alexander, John B. Col (USA-retired), *Winning the War, Advanced Weapons, Strategies, and Concepts for the Post 9-11 World,* New York, NY, September 2004.

Beason, Doug, *The E-Bomb*, Cambridge, Massachusetts: Da Capo Press, 2005.

Anton, Philip S., et.al., *The Global Technology Revolution – Bio/Nana/Materials Trends and their Synergies with Information Technology by 2020,* Santa Monica, CA: RAND Corporation, National Defense Institute, 2005

Geis, John Lt Col, *Directed Energy Weapons on the Battlefield, A New Vision for 2025,* Maxwell, AFB, AL, Center For Strategy and Technology, 2003.

Lofton, Victor Col. Defense Advanced Research Projects Agency (DARPA/USAF Operational Liaison: Special Assistant to the Director), interview by author during his visit to AWC/Horizons 21 guest lecturer, 29 November 2006.